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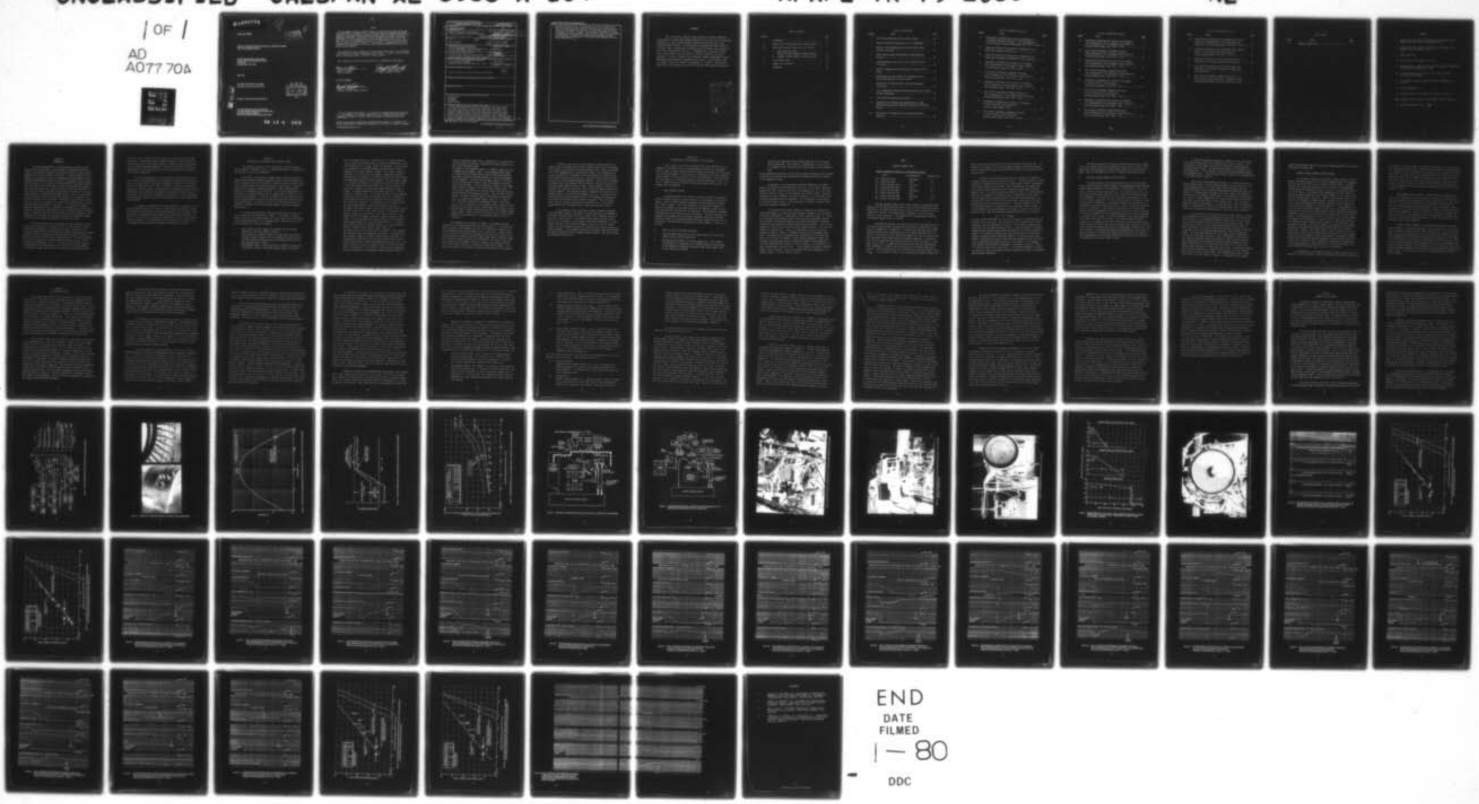

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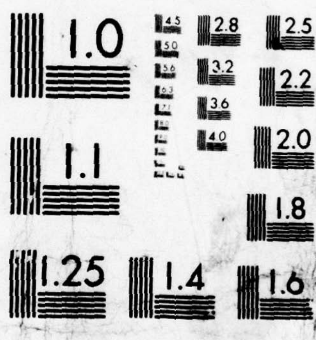

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TESTS OF AN IMPROVED ROTATING STALL CONTROL SYSTEM ON A J-85 TURBOJET ENGINE

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This report presents the results of testing a fast-acting rotating stall control system on a J-85 turbojet engine under sea level static conditions, both with and without inlet distortion. The control is an electronic feedback control system which uses unsteady pressure signals produced by pressure sensors within the compressor to detect incipient rotating stall and provide a correction signal when such a condition occurs. On the J-85 engine, the correction signal is used to drive a fast-response hydraulic actuator which operates intermediate stage compressor bleed doors over

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and inlet guide vane flaps. The performance of the stall control was tested by closing the bleed doors until rotating stall occurred or until the control anticipated stall and held the bleed doors open. The tests showed that the control is capable of anticipating stall before it occurs and keeping the engine completely clear of stall at speeds up to 80 percent of design speed. No tests were performed above 80 percent of design because opening the bleed doors at such speeds might aggravate the stall rather than clear it.

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FOREWORD

This is the final technical report prepared by Calspan Corporation on one phase of a multi-phase program sponsored by the Air Force Aero-Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Contract F33615-76-C-2092. The work herein was accomplished under Phase III of Project 3066, "Investigation of Rotating Stall and Turbine Heat Transfer in Axial Flow Turbomachinery; Phase III - Development of a Prototype Rotating Stall Control System", with Mr. Marvin A. Stibich, AFAPL/TBC, as Project Engineer. Dr. Gary R. Ludwig of the Aerodynamic Research Department, Calspan Corporation was technically responsible for the work. Other personnel were Dr. Joseph P. Nenni, Mr. James N. Dittenhauser, Mr. Alfred F. Gretch and Mr. Mario Urso all of Calspan, and Mr. Rudy H. Arendt of MGA Research Corporation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

SYMBOLS

B	detector bias level used in conditioning of compressor static pressure rise, millivolts (see Figures 4 and 5)
K	detector level gain used in conditioning of compressor static pressure rise (see Figures 4 and 5)
N	engine speed, rpm
N^*	rated speed of J-85 engine, 16,560 rpm
P_D	detector signals - amplitude of conditioned pressure fluctuations from control transducers, millivolts
P_R	system reference pressure used by stall control system, millivolts, (see Figure 5)
q_o	inlet dynamic pressure measured upstream of compressor face, in. H_2O
T	ambient temperature, °R
Δ	time delay factor in rotating stall control, (0.2 sec.)
ΔP_{REF}	compressor static pressure rise measured on outer casing, psi
θ	ambient temperature ratio, $\frac{T}{518.7}$

SECTION I

INTRODUCTION

The optimum performance of a turbo-propulsion system is usually achieved when the compressor is operating near its maximum pressure ratio. However, this optimum is generally not attainable because it occurs close to compressor stall and unstable flow conditions. In actual operation a stall margin must be provided to prevent the compressor from penetrating the stall boundary and developing destructive unsteady flow phenomena such as rotating stall and surge. This is usually done by prescheduling the engine controls. When an aircraft has a varied flight envelope, the prescheduling approach can lead to the requirement for a large stall margin to keep the engine out of stall under all possible transient and steady flight conditions. This stall margin represents a significant performance penalty. Also, in many instances of engine failure, rotating stall has been identified as a precursor to destructive unsteady flows in an engine. Furthermore, blade fatigue considerations will not allow a compressor to operate for prolonged periods in a large amplitude rotating stall mode. Clearly then, it is desirable to develop methods of estimating the stall boundaries of a compressor and if possible to develop an engine control system that can sense incipient destructive unsteady flows in a compressor and take corrective action to prevent compressor stall. Recognition of these goals has been the motivation for a continuing program of research that the AFAPL has sponsored at Calspan since 1962.

The work reported herein is concerned with the development of a fast acting control system which can sense the onset of rotating stall and keep the engine from operating in the rotating stall mode. The control is an electronic feedback control system which uses unsteady pressure signals produced by sensors within the compressor to detect incipient rotating stall and to provide a correction signal when such conditions occur. In a previous program the control was tested on a low speed research compressor and on a J-85-5 turbojet engine (References 1 and 2). The tests on the J-85 were successful in demonstrating that rotating stall can be controlled at engine speeds up to 70 percent of design speed and that the rotating stall detection system

worked very well. However the test results at 70 percent of design speed showed that, although the control acted fast enough to allow full recovery from rotating stall without engine damage or flameout, there was a noticeable change in engine operating parameters. Moreover the test results did not demonstrate that the stall control system can anticipate stall and prevent its occurrence completely.

In the current program, the installation of the rotating stall control on the J-85 was modified so as to decrease the response time of the control by a factor of ten. This report describes the results of a series of tests of the modified control on the J-85 engine. The test program had two objectives; the first was to investigate how much improvement in stall control performance can be obtained by substantially reducing the response time of the control, the second was to determine if rotating stall can be anticipated and eliminated by proper selection of the variables in the stall control detection system.

The report is divided into three major sections. In Section II, the basic operating principle of the stall control system is described. Section III presents the installation of the control system on the J-85 engine; both the original installation and the improved installation are described. In Section IV, the results of testing the improved stall control system on the J-85 are presented. Following these three major sections, a summary of the test program, and the conclusions reached are presented in Section V.

SECTION II

DESCRIPTION OF THE ROTATING STALL CONTROL SYSTEM

The operating principle of the rotating stall control system has been presented in References 1 and 2. A condensed description is repeated here for the sake of clarity and completeness.

The control is an electronic feedback control system which uses unsteady pressure signals produced by pressure sensors within the compressor to detect the presence of stall and provide a correction signal when stall occurs. In the prototype system, the correction signal is used to drive a hydraulic actuator which provides a mechanical operation on some variable geometry feature of the compressor to be controlled. In an initial demonstration of the control, the variable geometry was the stagger angle of stators in a low-speed research compressor. In tests on an aircraft J-85 jet engine, the controlled variable geometry features are compressor bleed doors and inlet guide vane flap deflection. In principle the stall control may be applied to any compressor or engine which has the variable geometry required to eliminate rotating stall.

The signal conditioning and processing subsystems of the stall control are shown in block diagram form in Figure 1. The signals at various stages in the circuit are shown schematically on the right side of the figure. In the following description, stator stagger angle is used as the stall correcting variable for illustrative purposes.

1. Time varying electronic signals are obtained from the pressure transducers within the compressor (Stage 1).
2. These signals are bandpass-filtered to remove steady state and low frequency variations (which are not associated with rotating stall) and high frequency contaminants such as instrument noise and rotor blade passage effects (Stage 2).
3. Each bandpass signal is then processed in an absolute value circuit (rectified) to obtain a conditioned detector signal, P_D (Stage 3).

4. Each conditioned signal, P_D, is then input to a voltage comparator circuit along with a second signal, P_R, which is proportional to the static pressure rise, ΔP_{REF}, across the compressor. The P_R signal is conditioned by a critically damped low pass filter so that it responds only to slowly varying changes. This signal is used to compensate the stall control for changes in compressor operating conditions such as compressor rotational speed and aircraft altitude. The comparator produces two output signals. The first signal, Stage 4, is obtained by comparing the conditioned detector signal, Stage 3, with the reference pressure signal, P_R. Only that portion of the Stage 3 signal which exceeds the reference pressure signal is passed. The second comparator output signal, Stage 5, is used to control an electronic gate. This signal activates the gate whenever the Stage 3 signal exceeds the reference level, P_R. The gate has been included in the circuit to ensure that the next component in the system, the integrator, is referenced to zero voltage whenever the input Stage 3 signal is below the reference level, P_R.

5. The Stage 4 and Stage 5 signals constitute the output from a typical detector channel in the stall control system. The prototype stall control contains ten such channels, each with two outputs. The Stage 4 outputs are summed to produce a composite analogue signal (Stage $\Sigma 4$) that represents the combined amount that all pressure sensor signals exceed the system reference pressure. The Stage 5 gate enabling signals are combined digitally in a logic circuit to produce a composite gate enabling signal (Stage $\Sigma 5$).

6. The output from the gate is fed into an integrator. The integrator gain and decay rate are independently adjustable. The output from the integrator (Stage 6) is then a signal which is obtained by integrating only those portions of the conditioned detector signals whose absolute values exceed the reference pressure level, P_R. With proper selection of P_R, the integrator output is nonzero only when stall is occurring or is very close to occurring in the compressor. When stall does occur, the integrator output increases rapidly to

provide a correction signal which is proportional to the severity of the stall which is occurring. The Stage 6 electronic signal is the basic stall correction signal.

7. The output of the integrator, Stage 6, is summed in opposition with a command position signal, Stage 7. This command position signal is obtained from the primary engine control system and represents the normal (unstalled) operating schedule for the variable geometry on the compressor. The output of the summer, Stage 8, is fed back into the primary engine control to move the compressor away from the stalled condition. In the illustration of Figure 1, the primary engine control is assumed to be a stator vane actuation servo. In this case the servo would act to move the stator vanes away from the stalled condition (reduce angle of attack). When the stall has been removed, the Stage 3 detector signals decrease below the reference level, P_R, causing the integrator input, (Stage ξ 4), to drop to zero. The output voltage of the integrator, Stage 6, then decays in a way which is controlled by the integrator decay circuitry, which consists of a time delay circuit, and two decay time constant circuits. When the Stage 6 signal has decayed sufficiently, the original command signal, Stage 7, resumes control allowing the engine to resume normal operation (stator vanes move to their original position in the illustration).

The integrator decay circuitry in Figure 1 is designed to prevent over-control of the engine after stall has been eliminated. It has been found that the control system performs very well in the presence of rotating stall if the integrator decay time constant is set to large values. However, operation of the control system with a long decay time constant will cause the controlled variable to overshoot when the primary engine controls command a change from a position inside the rotating stall boundary to one closer to the boundary or outside of the boundary. Under this condition the undecayed portion of the stall control signal will reinforce the engine control signal. Long decay time constants will increase the magnitude and duration of the overshoot.

In order to alleviate the above problem, the control system is designed so that it operates with two time constants, that is with a long decay time constant in the presence of rotating stall and with a short time constant once it has disappeared for a specified short period. The integrator decay circuitry consists of an electronic switch, an adjustable time delay circuit and a variable resistor that results in a short time constant when connected in parallel with the integrator feedback capacitor. The circuitry is designed to produce a short time constant when the electronic switch is closed and a long time constant when the switch is open. Stall pressures in excess of the reference level cause the electronic swtich to open and thereby establish the long time constant. The long time constant is maintained as long as the stall pressure signal is in excess of the reference level, P_R. If the stall pressure signal falls below the reference level, the integrator is switched back to the short time constant after a specific time delay. Thus, the system selects the fast recovery time (short time constant) only if the pressure signal remains below the reference level longer than the delay time, Δ .

In the prototype control system the mechanical operation commanded by the electronic console is performed by an electro-hydraulic servomechanism. In general, the servo consists of a flow control valve, a feedback potentiometer and a linear actuator. Two different servo systems have been used in tests on the J-85 engine. In the original installation (Reference 1) a small actuator was used in the mechanical feedback link of the J-85 fuel control system. The bill-of-material actuators on the engine were used to operate the variable geometry. In the current installation two larger, high-speed actuators were used to replace the bill-of-material engine actuators. Both servo systems are described in Section III.

SECTION III

INSTALLATION OF STALL CONTROL ON J-85-5 ENGINE

Stall control tests on the J-85 engine have been performed with two different installations for the variable geometry actuators on the engine. In both cases, the stall control detection system was the same, only the actuation system was changed. In this section, the features of the stall detection system, common to both test series, will be described first. This is followed by a description of the original actuation system of References 1 and 2. Finally, a description of the improved high-speed actuation system used in the current study is presented.

A. STALL DETECTION SYSTEM

As described earlier, the inputs to the stall control are unsteady pressure signals produced by sensors mounted in the compressor. On the J-85 engine, a total of eight pressure transducers are used to provide rotating stall control signals. All of the transducers are mounted to measure the pressure fluctuations on the inner surface of the compressor casing at four axial locations near the front of the compressor. Two transducers, separated circumferentially, are used at each axial location. The axial locations are governed by the geometry of the existing compressor casing which includes stiffener flanges on the external surface and stator support rings on the inner surface. The four axial locations can be seen in Figure 2. They are as follows:

1. Near the first stage rotor mid-chord.
2. Near the quarter-chord of the first stage stator, as close to the stator suction surface as possible.
3. Near the trailing edge of the second stage rotor. This location is determined by the presence of a stiffener flange on the outside of the compressor casing and the second stage stator support ring on the casing inner surface.

4. Between the second stage stator trailing edge and the third stage rotor leading edge. This location is determined by the location of the compressor bleed structure on the outer surface of the compressor case.

The circumferential locations of the control pressure transducers were selected so they do not interfere with mounting of the accessories and stall control on the compressor casing.

In addition to the eight control pressure transducers, two other pressure transducers were incorporated on the J-85. One of these transducers measured the static pressure rise across the compressor for use as the input reference pressure, ΔP_{REF}, to the rotating stall control system. The other transducer was used to measure the dynamic pressure, q_o, at the throat of the bellmouth upstream of the J-85 compressor. This transducer is not required by the stall control system. It was used simply to provide a measure of the mass flow through the compressor.

The rotating stall control operates by comparing the amplitude of conditioned signals, P_D, from the control pressure transducers in the compressor with the magnitude of a conditioned reference pressure signal, P_R. Prior to conditioning, the unsteady signals from the control transducers contain high frequency fluctuations caused by rotor blade passage and low frequency fluctuations associated with transient operation of the engine. Both of these components, which are associated with normal engine operation, could mask the presence of rotating stall. Thus, it is necessary to filter the control transducer signals to reduce or eliminate the high and low frequency components. The optimum filter characteristics were selected by observing the action of the control in response to tape recorded transducer signals from the engine operating under normal conditions and under stalled conditions. The filter characteristic selected is shown in Figure 3. In Reference 1 the tape recorded signals were also used to select the gain of various transducer signals, after filtering. The gain selections were left unchanged in the current program. They are listed in Table 1.

TABLE 1

DETECTOR CHANNEL GAINS

Control Transducer Location in J-85 Compressor Casing

Axial	Circumferential	Detector Gain
No. 1 Rotor Mid Chord	Top Right	10
No. 1 Rotor Mid Chord	Left	8
No. 1 Stator Quarter Chord	Top Right	5
No. 1 Stator Quarter Chord	Left	5
No. 2 Rotor Trailing Edge	Top Right	10
No. 2 Rotor Trailing Edge	Left	5
No. 2 Stator Trailing Edge	Top Right	7.5
No. 2 Stator Trailing Edge	Left	10

The tape recorded signals used to select detector channel gains were obtained with the engine operating with a clean inlet (no distortion screen). Nevertheless, the detector gains listed in Table 1 show a variation with circumferential location. (The highest gains correspond to the best signal quality for stall detection.) The reason for the circumferential variation in transducer signal quality is unknown.

The reference pressure, P_R, used by the control for comparison with the unsteady sensor signals was derived from the static pressure rise ΔP_{REF}, across the compressor. In general, it is desired that the magnitude of the reference pressure after conditioning vary with engine speed and inlet air density in the same way as the conditioned signals, P_D, from the control pressure transducers under normal unstalled operating conditions. The engine test cell at Calspan does not allow for control of inlet air density. (Some stall control tests at simulated altitude conditions have been performed by AFAPL, Reference 3) However, the variation of P_R with engine speed can be selected. Initial tests pointed out a deficiency in varying P_R linearly with ΔP_{REF}. At low compressor speeds, the system reference pressure became very

small and the control took action even in the absence of rotating stall. To prevent this occurrence, the system reference pressure circuit was modified so that the reference signal was always maintained above a prescribed minimum positive value.

A sketch of the system reference pressure variation in response to an input pressure variation is shown in Figure 4. The input pressure is shown starting at a negative value and rising to some positive value. Fluctuations in the input pressure are also shown. These fluctuations are removed from the system reference pressure by a one radian/sec second-order critically-damped filter. If the input pressure is negative or zero, the system reference pressure is maintained at a positive value, B, selected by a bias control. Once the input pressure becomes positive, the system reference pressure is increased above the bias level by an amount equal to the value of the input pressure multiplied by the detector gain, K. Both the detector bias level, B, and detector gain, K, are variable in this prototype control system. On the J-85 engine, the static pressure rise, ΔP_{REF}, is always zero or some positive value. Thus the conditioned reference pressure, P_R, is given by

$$P_R = B + K \Delta P_{REF}$$

The stall control performance on the J-85 was tested for three different combinations of bias and gain. The variation of P_R with engine speed is shown in Figure 5 for each combination of B and K. Also shown are measured data points for the on-schedule detection level, P_D, which represent the combined background noise during normal engine operation from all control transducer signals. The reference pressure curve, P_R, must be above the normal background level data to avoid unwarranted action by the stall control system. However, locating the P_R curve too far above the background level will allow stall to develop before corrective action is initiated. In the original stall control tests reported in Reference 1, the upper P_R curve (B = 240 mv, K = 0.084) was used in all of the tests. In the current program, all three P_R curves were used to investigate whether rotating stall could be anticipated and eliminated completely.

The above description of the stall control detection system is common to both the original test series of References 1 and 2 and the current series. However the variable geometry actuation system differed in the two test programs. These are described below, with the original system present first.

B. ORIGINAL VARIABLE GEOMETRY ACTUATION SYSTEM

The output from the stall detection system is an electronic signal which is used to govern an electro-hydraulic servomechanism for operating some variable geometry features on the compressor to be controlled. On the J-85 engine, which has an eight stage compressor, the variable geometry consists of the inlet guide vanes and bleed doors on the third, fourth, and fifth stages of the compressor. The positions of the guide vanes and bleed doors on the J-85 are normally controlled by the fuel control system as a function of engine rpm and inlet air temperature. A mechanical feedback cable between the variable geometry actuators and the fuel control is used to ensure that the proper position is maintained. In the original installation, the rotating stall control system was incorporated into the main J-85 control system by replacing the mechanical feedback cable with another mechanical cable which was operated by the stall control system. This cable replacement was the only change made in the normal J-85 fuel control system. The variable geometry actuators continued to be operated by the fuel control but the response could be modified by action of the stall control on the feedback loop. Essentially the stall control deceived the engine fuel control into performing the desired stall control functions. The principal advantage of incorporating the stall control in this way was that it minimized the engine modifications which were required. A major disadvantage was that response speed of the installation was limited by the response of the J-85 fuel control system.

A sketch of the mechanical/hydraulic feedback loop with the rotating stall control incorporated in its original form is shown in Figure 6. The lower portion of this figure shows the bill-of-material variable geometry system for the J-85 engine. An operating description of that system will not be presented here. It is sufficient to point out the above-mentioned change in the feedback cable. The rotating stall control system is shown schematically in the upper portion of Figure 6.

Under normal engine operating conditions, it is necessary that the modified engine follow a variable geometry schedule which is the same as that of the unmodified engine. This was accomplished by mounting a precision linear potentiometer on the existing variable geometry control bellcrank (see Figure 6). The potentiometer provides an electronic signal that represents the position of the original feedback cable. In the absence of rotating stall, this electronic signal commands the stall control servo to move the new feedback cable to the normal position of the original cable. Thus, the normal operating schedule is maintained. If a stall does occur, the stall correction signal is electronically combined with the potentiometer signal to command new bleed door (and guide vane) configurations to control the stall condition.

The installation of the stall control on the J-85 engine has a limitation generated by the overall configuration of that engine. The location of the bleed doors on the intermediate compressor stages will only allow control of stalls which originate on the first two or three compressor stages. Such stalls are most likely to occur at engine speeds between idle and approximately 80 percent of rated speed, where the bleed doors are normally scheduled to be open in order to provide matching between the front stages and rear stages. (For stall-free operation, the front stages require a higher mass flow than the rear stages can accept.) Thus, the operation of the stall control system was ultimately tested by arbitrarily closing the bleed doors at these engine speeds, and observing if the stall control prevents the occurrence of rotating stall by limiting how far the doors can be closed, or by rapidly opening the doors if a stall does begin to form. The arbitrary command for closing the bleed doors is generated by an auxiliary electronic command signal within the stall control system. This command signal, which is shown as an input to the stall control in Figure 6, is combined with the variable

geometry potentiometer signal to provide off-schedule performance of the bleed doors and inlet guide vanes.

C. IMPROVED VARIABLE GEOMETRY ACTUATION SYSTEM

In the current installation of the stall control system on the J-85 engine, the response speed of the system was increased greatly by eliminating the J-85 fuel control from the stall control actuation system. A schematic drawing of the improved installation is shown in Figure 7 and photographs of the hardware are presented in Figures 8, 9, and 10. The modified installation is as follows. The hydraulic output generated by the fuel control to provide on-schedule operation of the variable geometry is still used to drive the J-85 variable geometry actuators. However, these actuators are not connected to the compressor variable geometry. Instead, they are used to position a linear potentiometer from which the required electronic signal for normal on-schedule performance is derived (Figure 8). This on-schedule signal, which can be filtered to reduce electronic noise, is combined within the rotating stall control with the existing stall control signal and off-schedule performance signal to give a single electronic output from the stall control console. This combined signal is used in conjunction with a new flow-control valve (Moog Series 32 Servovalve) to control two new high-speed actuators on the compressor variable geometry system (Figure 9). The new actuators were fabricated at Calspan. The existing hardware links between the new hydraulic actuators and the compressor guide vanes and bleed doors did not require modification. However, a new larger capacity source of hydraulic power for the actuators (Figure 10) was required because the small unit on the original installation was not adequate to drive the actuators. The modified variable geometry servo-system was designed to generate 100 percent bleed door travel in about 25 milliseconds. This is substantially faster than the capability of the normal engine bleed door control servo. The latter was found to generate 100 percent bleed door travel in about 400 milliseconds.

The improvement in the response speed of the bleed doors on the J-85 compressor is shown in Figure 11 where the original and the current installations

are compared. The figure shows the measured time response of the bleed doors to a large amplitude stall which starts with the bleed doors closed 80 percent. The response curves also represent the configuration of the flaps on the inlet guide vanes since these are connected mechanically to the bleed door actuation mechanism. There are two response curves for the current installation, one with a rate limiter on the stall control output and one with the rate limiter removed. The rate limiter was installed for the initial series of tests in the current program to lessen the chance of hardware failure in the bleed door actuation system.

The response curves of Figure 11 show that the bleed doors do not begin to move immediately when stall inception is detected. Rather, there is a time delay between stall inception and initial bleed door motion. This time delay occurs because of lags in the various components of the mechanical-hydraulic actuation system and should be made as small as possible. Large time delays will allow the stall to develop fully before any corrective action occurs on the compressor. The rate at which the bleed doors move after the initial time delay is also important because the combination of initial time delay plus final rate of motion determines the overall time required for full corrective action on the compressor.

As can be seen in Figure 11, the current installation of the stall control provides a substantial improvement in response speed of the J-85 bleed doors to correction signals from the stall control system. The total time required to open the bleed doors from an initial position 80 percent closed has been reduced from 376 milliseconds for the original installation to a minimum of 36.5 milliseconds for the current installation without rate limiting. With the rate limiter installed, the corresponding time is 76.6 milliseconds which is still a large reduction in total response time. The first four control tests during the present program were performed with the rate limiter installed on the control system. The last three control tests were performed with the rate limiter removed.

SECTION IV
STALL CONTROL TESTS

The current test program on the rotating stall control system had two objectives. The first was to investigate how much improvement in performance can be obtained by substantially increasing the response speed of the variable geometry on the J-85 engine. The second objective was to see if rotating stall could be anticipated and eliminated by proper selection of the conditioning parameters for the reference pressure. The test series on the modified control consisted of eight tests. The first test was performed with the J-85 engine in its normal configuration. This test was used for engine checkout and also to provide baseline data for the output from the control pressure transducers when the engine is operating normally. The remaining seven tests were performed with the stall control system in operation with different settings for several of the control parameters. In addition, three of the control tests were performed with no inlet distortion and four of the tests were performed with 180 degree circumferential inlet distortion.

The distortion screen, shown in Figure 12, was mounted just upstream of the compressor face. The inlet bellmouth is removed in this photograph. During the tests, the bellmouth was installed as shown in Figure 10. The wire diameter in the distortion screen is 0.035 inches and the mesh size is 8 wires per inch, providing a porosity of 52.1 percent open area. The magnitude of the distortion was not measured. However, it falls within the range of values reported in Reference 4 where a series of distortion tests were performed on a J-85 engine. Screens of similar construction with mesh sizes of 7-1/2, 8-1/2 and 9 wires per inch (porosities = 57.4%, 49.8% and 39.7%, respectively) were tested in that work. The distortion screen was positioned so that four of the control pressure transducers were in the wake of the screen and four were not. The four control transducers outside of the screen wake are labeled in Figure 12. The four transducers in the screen wake are not visible in this photograph. They are located circumferentially just below the labeled monitor pressure transducer.

The J-85 was stalled in two ways; by closing the bleed doors at constant engine speed, and by decelerating the engine with the bleed doors partially closed at the beginning of the deceleration. During these tests, data were recorded directly on Brush Recorder charts and also on a 14 channel Sangamo FM tape recorder. The tape recorder was operated at 60 ips (20 KHz bandwidth) to obtain records which could be expanded in time by playback at slower speeds. Before proceeding with a discussion of the current results, an example of an expanded time record from the past J-85 stall control tests will be presented to provide a basis for comparison.

The response of the original control installation to rotating stall inception on the J-85 engine is illustrated in Figure 13. The records in this figure were obtained by closing the J-85 bleed doors slowly to induce rotating stall at constant engine speed. This particular set of records is from a test at the highest corrected engine speed (71.8%) used in the original test series. The top two records in Figure 13 show the bleed door position and the compressor static pressure rise, ΔP_{REF}, across the J-85 compressor. The unsteady detector pressure signals generated by half of the eight control pressure transducers are shown in the bottom four records. The high frequency portions of these signals have been filtered as shown in Figure 3.

A vertical dashed line labeled "Reference Time Zero" has been included on Figure 13 to indicate the approximate time at inception of rotating stall. The position of this line corresponds to the first indication of rotating stall in any of the detector pressure signals. Inspection of this set of expanded time records shows that the duration of the stall, measured from time zero until stall has disappeared, was about 325 milliseconds. Inspection of the bleed door position record shows that there is a delay between reference time zero and the time at which the bleed doors begin to open. For this case, which was the most severe stall in the original test series, the delay was approximately 30 milliseconds. At the same time the compressor static pressure rise began to drop after a delay of only 10 milliseconds. Thus, although the control opened the bleed doors fast enough to allow full recovery without

damage or flameout there was a noticeable change in engine operating parameters. Thus, it was concluded that it would be desirable to increase the speed at which the bleed doors open to minimize these variations in engine operating parameters.

The current tests were designed to study how much improvement could be obtained by increasing the bleed door response rate and also to see if rotating stall could be eliminated completely. Analysis of the data shows a substantial improvement in reducing the duration of stalls and that large amplitude rotating stall can be eliminated by proper setting of the control parameters. The results of the tests are described in the following paragraphs.

One series of stall control tests on the J-85 was performed without inlet distortion. Figure 14 shows a summary of the bleed door positions observed at rotating stall inception with undistorted inlet flow. The inception points were obtained by closing the bleed doors to induce a stall at constant engine speed. The inception boundary agrees well with the more limited data found in previous tests with the original installation of the stall control on the J-85. The original tests covered an engine speed range between 48 and 62 percent of rated engine speed. As noted in Reference 1, the stalls become progressively more severe as the engine speed is increased and it was felt that the most prudent course of action was to limit the severity of the stalls in those preliminary tests. In the current tests, the speed range used for the stall tests was extended to 75 percent of rated engine speed without any difficulties. Moreover, stalling the compressor at the higher engine speeds required detuning the stall control by using the highest system reference level or P_R curve (B = 240 mv, K = 0.084) shown in Figure 5. As can be seen by inspection of the data points in Figure 14, when the lowest P_R curve (B = 180 mv, K = 0.040) was used the highest engine speed for which stall was observed was near 60 percent of rated speed. At higher engine speeds the control held the bleed doors open and prevented stall inception. With the intermediate P_R curve (B = 150 mv, K = 0.084) the highest engine speed at which compressor stall occurred was approximately 72 percent of rated speed. Here again, at higher engine speed the stall control held the bleed doors open far enough to prevent rotating stall inception.

In addition to the control tests on the J-85 with undistorted inlet flow, a series of tests was performed with a 180 degree distortion screen installed in the inlet to the engine. Figure 15 is a summary of the stall inception boundary found in these tests. As with the undistorted inlet flow tests, this inception boundary agrees well with the more limited preliminary tests reported in Reference 1. With the distorted inlet flow it was possible to stall the compressor at the higher engine speeds when the stall control was set to use the intermediate, P_R, curve of Figure 5 (B = 150 mv, K = 0.084). However, at engine speeds up to 75 percent of rated speed, when stalls did occur they were of limited amplitude and were cleared in less than 90 milliseconds. These excellent results prompted a stall test in which the engine speed was increased to the maximum possible (79.4 percent) without having the bleed doors close on their normal schedule. This particular stall was not cleared rapidly. In this case the stall lasted for 1.06 seconds even though the bleed doors were opened fully in approximately 80 milliseconds after the first stall cell was detected. Apparently once this severe stall has developed, it cannot be cleared by changing the existing geometry on the J-85 engine. Instead the engine decelerated on its own to 63.1 percent of rated speed before the stall was cleared. Once the stall was cleared, engine operation appeared to be normal. Following this stall test series, a final series of stall anticipation tests were performed with the most sensitive P_R curve (B = 180 mv, K = 0.040) in Figure 5. With this P_R curve, the highest engine speed for which stall was observed was near 64 percent of rated engine speed. At higher engine speeds, the control held the bleed doors open far enough to prevent stall inception when attempts were made to stall the compressor by commanding the bleed doors to close. Detailed records of the stall and stall anticipation tests are presented in the following paragraphs.

Figures 16 through 29 are representative multi-channel strip recorder charts which illustrate the performance of the control system when the compressor is forced into rotating stall by closing the bleed doors at constant engine speed. The records include corrected engine speeds of approximately 70, 75 and 80 percent of rated speed. Lower speed stalls are not presented since they were

not as severe and were cleared rapidly by the stall control system. At corrected engine speeds of 70 and 75 percent, three sets of data records are presented (Figures 16 through 27); one set with 180 degree inlet distortion and with the rate limiter in operation (see Figure 11), one set with 180 degree inlet distortion without the rate limiter, and one set with no inlet distortion and without the rate limiter. Figures 28 and 29 present records from the compressor stall at 79.4 percent of rated engine speed. The compressor was allowed to stall only once at this engine speed. The test conditions were 180 degree inlet distortion with the rate limiter in operation on the stall control system.

Each stall in Figures 16 through 29 is presented on two consecutive figures. The first figure presents strip chart records obtained directly while the test was in progress and includes approximately 10 seconds of test results. The second figure presents essentially the same results on a much expanded time scale which covers approximately 320 milliseconds. The expanded time records were obtained by replaying at low tape speed, FM tape records of the tests which were recorded at high tape speed. In each figure six recorded traces are shown as a function of time. The time increases from left to right and the time scale is indicated just below the second record from the top. The upper five records on each of Figures 16 through 29 present the same variables. Each of these records is discussed below starting with the top record as number one.

(1) Engine RPM (Uncorrected) - This is record of the engine speed in percent of design speed. It is obtained from a magnetic pickup which counts blade passage of the first stage rotor. The record has not been corrected for compressor inlet temperature.

(2) Off-Schedule Command - This command is an arbitrary signal generated by the operating engineer. It is used to close the bleed doors (and open the inlet guide vanes) in order to force the compressor into rotating stall. In these tests, this command was used to stall the compressor by slowly closing the bleed doors while engine speed was held constant.

(3) Bleed Door Position - This is a record of the position of the linear potentiometer on the variable geometry bellcrank. It is representative of the bleed door position as well as the configuration of the inlet guide vanes since both are connected mechanically.

(4) Compressor Static Pressure Rise, ΔP_{REF} - This is a record of the pressure difference between static pressure taps located on the outer casing upstream and downstream of the compressor. The control system pressure, P_R, is derived from ΔP_{REF} as explained previously. The bias, B, and gain, K, which determine the shape of the system reference pressure, P_R, curve (see Figure 5) are noted just below the first record.

(5) Stall Control Integrator Output - This is a record of the electrical output from the stall control system. When this output is zero (top of the strip record) the bleed door position in record 3 should follow the off-schedule command in record 2. A non-zero output from the integrator will open the bleed doors in proportion to the magnitude of the output. A very rapid increase in the integrator output, such as when large amplitude rotating stall occurs, opens the bleed doors at a rate determined by the capability of the hydraulic actuation system (see Figure 11).

The sixth record in the directly recorded strip charts differs from that in the expanded time strip charts. These records are as follows.

(6) Directly Recorded

Compressor Inlet Dynamic Pressure, q_o - This is a record of the dynamic pressure at the throat of the bellmouth upstream of the J-85 compressor. It is proportional to the square of the mass flow at the compressor inlet.

(6) Expanded Time

Detector Pressure Signal - No. 1 Rotor, Top Right - This is a record of the signal from one of the eight control pressure transducers mounted in the compressor outer casing. This signal along with

signals from the other seven transducers are used by the control system to detect the presence of rotating stall. If the amplitude of the fluctuations in any one of these signals becomes larger than the system reference pressure, P_R (Figure 5), the control opens the bleed doors until the fluctuation amplitude decreases below the reference level. After stall disappears for a specified time (0.2 seconds in these tests), the bleed doors return to their original position. The rate at which the bleed doors return is specified by the decay rate of the integrator in the control system. In these tests the time constant for the decay rate was 2 seconds. The recorded signal in this record has been filtered as indicated in Figure 3.

The vertical scales for all of the records discussed above are presented on the right side of each record.

The first series of stall control test records are presented for a nominal engine speed of 70 percent of rated speed (Figures 16 through 21). The test conditions for the stall shown in Figures 16 and 17 were 180 degree circumferential inlet distortion and the rate limiter in operation on the stall control system. As can be seen in Figure 16, the effect of the stall on the engine was relatively small. There was a momentary drop in compressor static pressure rise and inlet dynamic pressure. In addition, there was a small drop in engine speed, about 2 percent, just after stall was cleared. The expanded time record of this stall (Figure 17) shows that the rotating stall was limited to approximately seven cells in a duration of about 80 milliseconds and that the stall was cleared slightly after the bleed doors were fully open. The bleed door response to the integrator output was delayed by about 15 milliseconds and the time to open the doors completely after the integrator signal responded to the stall was approximately 70 milliseconds. A similar stall test with the rate limiter removed is shown in Figures 18 and 19. In this case, only four small stall cells occurred in a duration of approximately 35 milliseconds. The stall was cleared before the doors were fully open. The time to open the doors

after the integrator began to respond to the stall was approximately 55 milliseconds. Moreover the momentary drop in ΔP_{REF} and engine speed were very small in this case. Corresponding test results without inlet distortion are shown in Figures 20 and 21. Here the stall control performed at least as fast as it did in the presence of inlet distortion. These results are a dramatic improvement over the earlier test results (Figure 13) where the speed of the bleed door response was limited by the capability of the J-85 fuel control system.

Some further tests were performed at 70 percent of rated engine speed to investigate the small decrease in engine speed observed in Figures 16,18, and 20. This was done by closing the bleed doors to a position just prior to stall inception and then opening them rapidly by removing the signal for closing the doors. It was found that engine speed drops about 2 percent due to opening the doors even when rotating stall is absent. This is about the same amount as that observed in the stall tests. Thus the drop in engine speed during the stall test appears to be due to opening the bleed doors rather than the occurrence of rotating stall.

Results for the stall control tests at a nominal engine speed of 75 percent are presented in Figures 22 through 27. The most interesting results are the expanded time records (Figures 23, 25, and 27). With the rate limiter in operation and the 180 degree distortion screen in the engine inlet, eight stall cells occurred over a duration of approximately 90 milliseconds (Figure 23). The bleed doors opened completely in 81 milliseconds in this case. Removal of the rate limiter (Figure 25) decreased the time for the bleed doors to open to just over 40 milliseconds. However, eight stall cells (one very small) still occurred and the stall duration was again near 90 milliseconds. With no inlet distortion and the rate limiter removed (Figure 27) only a slight improvement is noticeable (seven stall cells over a duration of about 78 milliseconds). By themselves, these are excellent results for the performance of the stall control system in eliminating rotating stall once it occurs. However, the stalls did not clear until after the bleed doors were open for a short time, even with the fastest available response of the bleed

doors. This suggests that problems may be encountered if rotating stall is permitted to occur at higher engine speeds. The results from one such stall are shown in Figures 28 and 29.

Figures 28 and 29 show the response of the stall control system to stall at a corrected engine speed of 79.4 percent. This is the highest engine speed for which the bleed doors did not begin to close on their normal schedule under the action of the J-85 fuel control system. This stall was obtained with the 180 degree distortion screen in the engine inlet and with the rate limiter in operation on the stall control system. The presence of the rate limiter means that the bleed doors did not respond at the maximum rate available. However, the results presented previously for 75 percent corrected engine speed suggest that a result similar to that shown in Figures 28 and 29 would have been obtained with the rate limiter removed. The direct records of this stall (Figure 28) show that the stall lasted a considerable time (1.06 seconds) even though the bleed doors were opened completely in about 80 milliseconds (Figure 29). While the stall was occurring, the pressure drop across the compressor caused the engine to decelerate on its own to a corrected speed of approximately 63 percent before the stall was cleared. The additional engine deceleration in Figure 28 about a second after the stall was cleared was effected when the test engineer chopped the throttle. The time at which the throttle was chopped is indicated on Figure 28. In addition to the hard stall, Figure 28 shows the response of the control to three small amplitude stalls after the throttle was chopped. These occurred because the off-schedule command was not reduced fast enough by the operator to prevent low speed stalls after the engine decelerated. The results in Figures 28 and 29 suggest that once this stall has developed, it cannot be cleared by changing the existing geometry on the J-85 engine without first causing a substantial engine deceleration. However once the stall was cleared, engine operation appeared to be normal. In fact three more engine tests were performed after this stall occurred without any indication of engine damage. (Some of the insulators used to isolate the stall control pressure transducers from the J-85 compressor case were found to be defective after this hard stall, but these were repaired and no further problems were encountered.)

The results presented in Figures 16 through 29 were obtained with the reference pressure level, P_R, purposefully set at high enough levels to allow the compressor to stall. This was done to investigate the performance of the modified stall control in clearing rotating stall once it had started. The results showed that for engine speeds up to 75 percent ($\approx$12,400 rpm) of rated speed, the stall control acted fast enough to clear rotating stall before it had a noticeable effect on the J-85 engine. However the test at 79.4 percent of rated engine speed showed that the control is not fast enough to clear this stall without first allowing a substantial deceleration of the engine. There are two possible solutions to controlling a high speed stall such as this. The first is to increase the range of control available to the stall control system. On the J-85 this would require increasing the existing bleed air mass flow or including provision for bleeding air at the rear of the compressor or, perhaps, incorporating the stall control in the fuel flow control system. None of these were practical on the existing engine. The second possibility is to have the stall control system anticipate and eliminate the stall before it develops. The latter possibility was tested and found to work well at high engine speeds. The results are presented below.

Figures 30 and 31 illustrate the performance of the stall control system when the reference pressure level is set low enough to anticipate rotating stall (B = 180 mv, K = 0.040). These records were obtained by attempting to close the bleed doors at constant engine speed with the stall control reference pressure level set as noted above. The complete strip chart records of these tests are very long. They start with the bleed doors fully open, and both the off-schedule command and the integrator output at zero. The central portion of each test is shown in Figures 30 and 31. Here the off-schedule command is at its maximum (fully closed) and the integrator output has increased sufficiently to hold the bleed doors open far enough to prevent rotating stall inception. In each of Figures 30 and 31, the bleed door position at which stall occurs is shown as a dashed line. These positions were taken from other tests in which rotating stall was allowed to occur by choosing higher values of the reference pressure level, P_R.

Summaries of all the stall anticipation test results are presented in Figure 32 for undistorted inlet flow and in Figure 33 for 180 degree inlet distortion. As can be seen in these figures, with the bias, B, set at 180 millivolts and the gain, K, set at 0.040, the stall control held the bleed doors open far enough to prevent stall inception for engine speeds of 70 percent and higher. Some additional tests at lower engine speeds and with a higher P_R setting (B = 150 mv, K = 0.084) were also successful in preventing stall inception. However, the results in Figures 32 and 33 for these tests show that the bleed door excursions approach the stall inception boundary close enough that rotating stall may have occurred if the test duration had been extended for a longer time period. In any event, the stall anticipation tests are considered to be successful in that they demonstrated that with proper setting of the reference level, the stall control system is capable of anticipating and preventing the large amplitude rotating stall which occurs at high engine speeds.

The above test results were all obtained by running the J-85 at constant speed and closing the bleed doors until rotating stall occurred or until the control anticipated stall and held the bleed doors open. The stall control was tested using seven of the eight available pressure transducers in the J-85 compressor casing to detect rotating stall. (The eighth transducer was found to be defective early in the test program and was not used in these tests.) In addition to the test results just presented, some tests were performed to investigate the effect of reducing the number of pressure transducers used to detect rotating stall. It was found that satisfactory performance, almost as good as that presented above, could be obtained by using only two transducers separated circumferentially and situated axially between the second stage stator trailing edge and third stage rotor leading edge (see Section III and Figure 2). Combinations of other transducers located closer to the front of the compressor did not give the stall control adequate input to provide satisfactory performance. Stalls were detected but were not cleared as fast as they were with the above two transducers.

Finally, as in Reference 1, some tests were done to study the performance of the control during engine deceleration. In these tests, the engine speed was set at 80 percent of design speed and the bleed doors were closed either a preset amount or else as far as they would go depending on the reference level setting of the stall control. The engine was then decelerated by chopping the throttle to its idle position. The deceleration induced rotating stall in the compressor at some point during the deceleration. With the most sensitive setting for the reference pressure level (B = 180 mv, K = 0.040), it was found that the highest engine speed at which rotating stall occurred was approximately 70 percent of design speed and that the stall amplitudes and durations were very small. An expanded time record of one such stall is shown in Figure 34. A portion of this record prior to stall has been deleted in order to present the record on one page. Note that rotating stall inception did not occur until the engine had decelerated to under 70 percent ($N/N^* \sqrt{\theta} = 68.7\%$) of design speed. The rotating stall amplitude is similar to the results from the tests at constant engine speed (Figures 19 and 21, $N/N^* \sqrt{\theta} \approx 70\%$). These results agree well with what one would expect from inspection of the stall anticipation tests summarized in Figures 32 and 33. Thus it is concluded that the performance of the stall control in clearing stalls induced by moderate transients such as in the engine decelerations is about as good as it is in anticipating or clearing rotating stall under the relatively constant conditions used for the main body of the tests.

SECTION V
SUMMARY AND CONCLUSIONS

An improved version of a rotating stall control system has been tested successfully on a J-85-5 turbojet engine. Past tests (References 1 and 2) had pointed out the desirability of increasing the response speed of the control. In this study, the installation of the stall control on the J-85 was modified so as to decrease the response time of the control by a factor of ten over that attained in the past tests. The modified control was tested to see if the decreased response time improved the ability to clear rotating stall once it has started, and also to see if rotating stall could be anticipated and eliminated by proper selection of the variables in the stall control detection system.

The tests were performed under sea level static conditions, both with and without inlet distortion. The stall control was installed to override the normal operating schedule of the compressor bleed doors and inlet guide vanes on the J-85. The tests were limited to engine speeds at or below 80 percent of design speed because of the overall configuration of the engine. The location of the bleed doors on the intermediate compressor stages will only allow control of stalls which originate on the first two or three compressor stages. Such stalls are most likely to occur at engine speeds between idle and approximately 80 percent of rated speed, where the bleed doors are normally scheduled to be open in order to provide matching between the front stages and rear stages. The operation of the stall control system was tested by arbitrarily closing the bleed doors at these engine speeds, and observing if the stall control prevents the occurrence of rotating stall by limiting how far the doors can be closed, or by rapidly opening the doors if a stall does begin to form. A similar procedure was not applied above 80 percent of rated speed because clearing stalls at these speeds would probably require unloading the rear compressor stages. In this case opening the bleed doors on the intermediate stages would only aggravate the stall, not clear it.

The J-85 was stalled in two ways, first by closing the bleed doors at constant engine speed, and second by decelerating the engine with the bleed

doors partially closed at the beginning of the deceleration. In the constant speed tests it was found that the control can anticipate and eliminate rotating stall completely at engine speeds between 65 and 80 percent of design. The deceleration tests showed the same capability at engine speeds between 70 and 80 percent of design. At speeds lower than 65 to 70 percent of design, it was possible to stall the compressor but the amplitude and duration of the stalls were very small and had no noticeable effect on the engine. Moreover, with the control set to anticipate stall, normal unstalled operation of the engine was unaffected.

Additional tests were performed in which the stall control was intentionally detuned to allow the compressor to stall. This was done to investigate the performance of the modified stall control in clearing rotating stall once it had started. The results showed that for engine speeds up to 75 percent ($\approx$ 12,400 rpm) of rated speed, the stall control acted fast enough to clear rotating stall before it had a noticeable effect on the J-85 engine. However a test at 79.4 percent of rated engine speed showed that the control is not fast enough to clear this stall without first allowing a substantial deceleration of the engine. There are two possible solutions to controlling a high speed stall such as this. The first is to increase the range of control available to the stall control system. On the J-85 this would require increasing the existing bleed air mass flow or including provision for bleeding air at the rear of the compressor or, perhaps, incorporating the stall control in the fuel flow control system. None of these were practical on the existing engine. The second possibility is to have the stall control system anticipate and eliminate the stall before it develops. As described above, the latter possibility was tested and found to work well at high engine speeds.

In view of the excellent test results obtained on the J-85 engine, it is recommended that the stall control be developed further on another engine with hardware more suitable for the control of stalls over the complete range of engine speeds. The control function could be applied to variable geometry, to fuel flow control or to a combination of both. It may well be that the most suitable adaptation of the stall control would be integration with an engine and control system which is still under development.

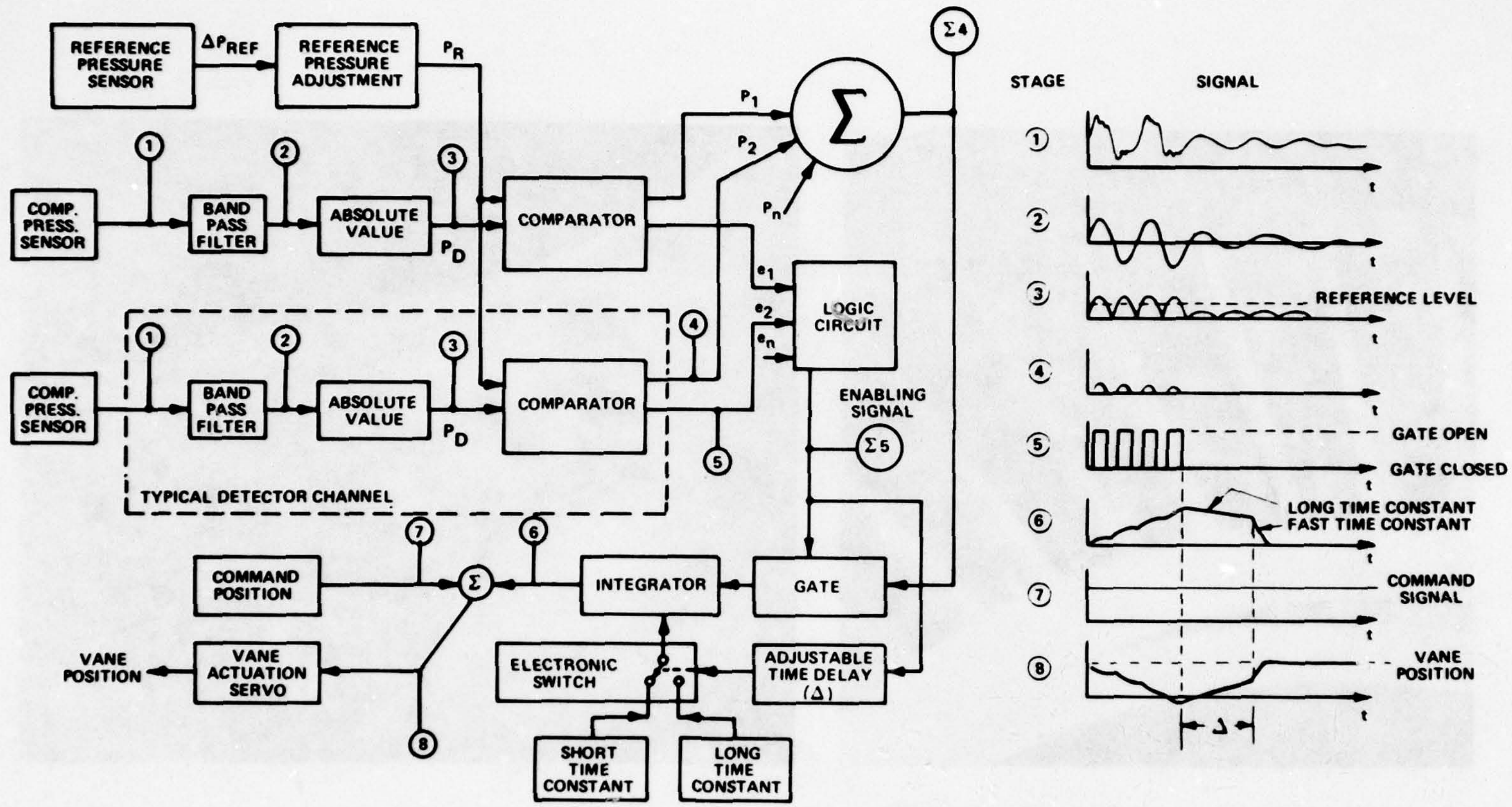


Figure 1 BLOCK DIAGRAM OF ROTATING STALL CONTROL SYSTEM

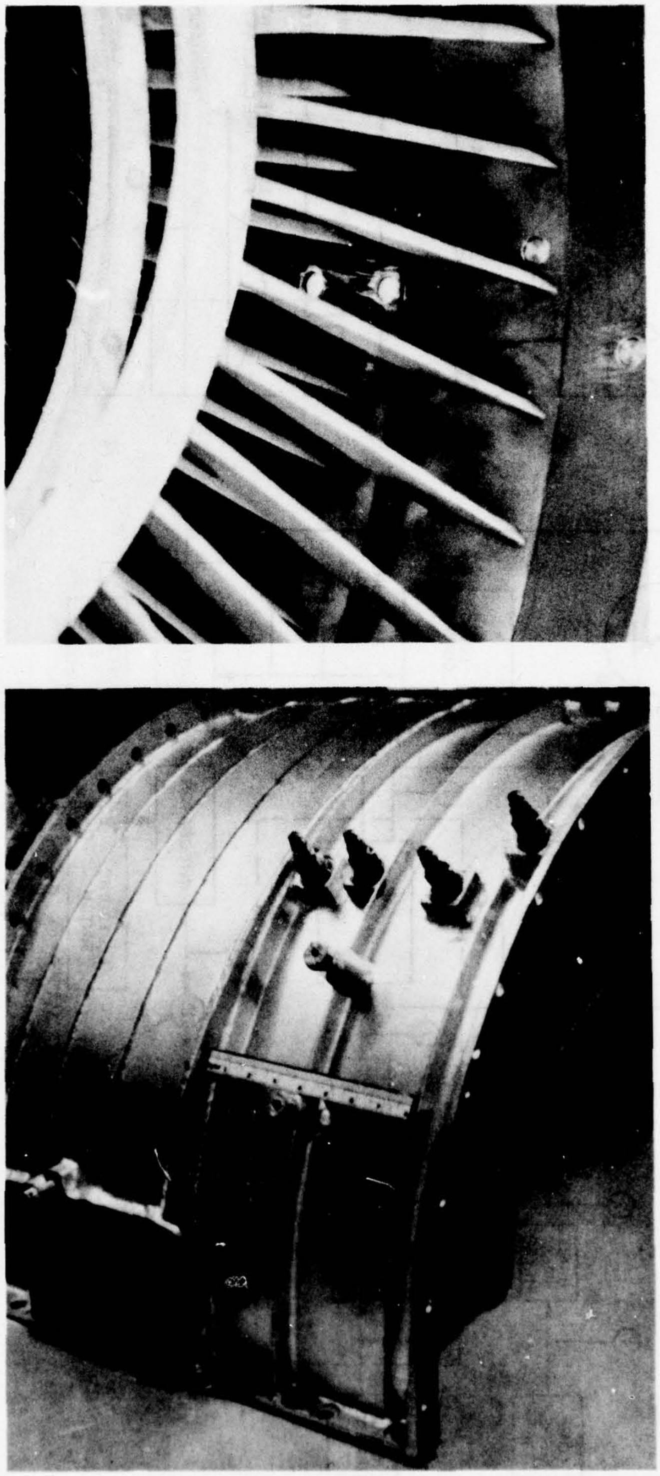


Figure 2 PRESSURE TRANSDUCER INSTALLATIONS IN J-85 COMPRESSOR

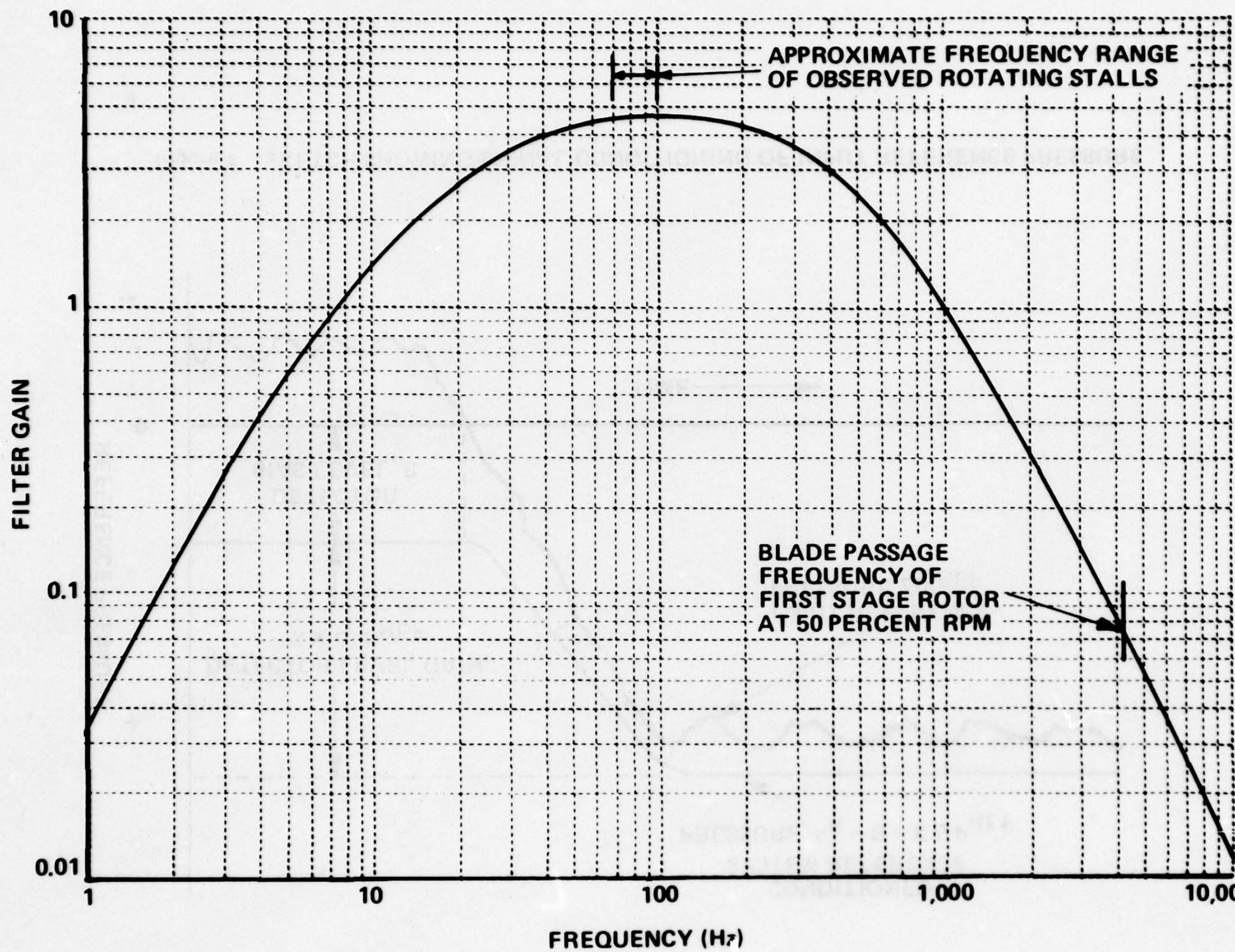


Figure 3 DETECTOR FILTER CHARACTERISTICS USED FOR STALL CONTROL TESTS ON J-85 ENGINE

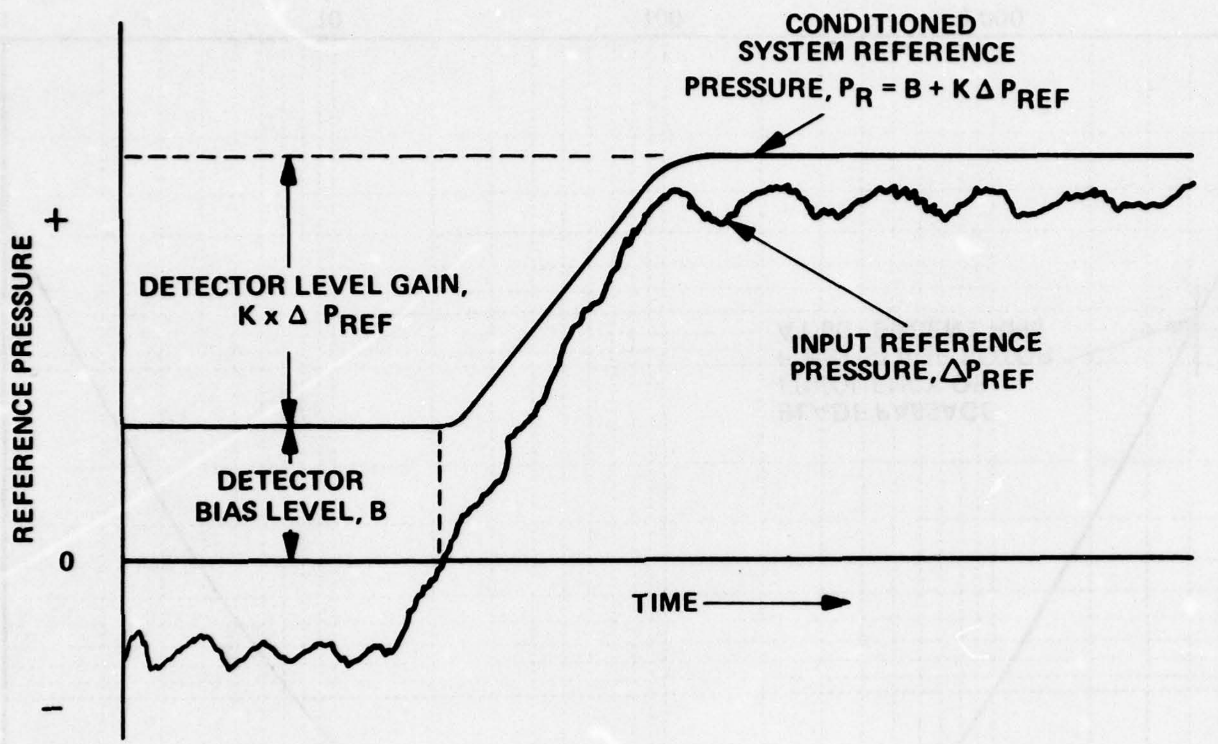


Figure 4 SKETCH SHOWING SIGNAL CONDITIONING OF INPUT REFERENCE PRESSURE

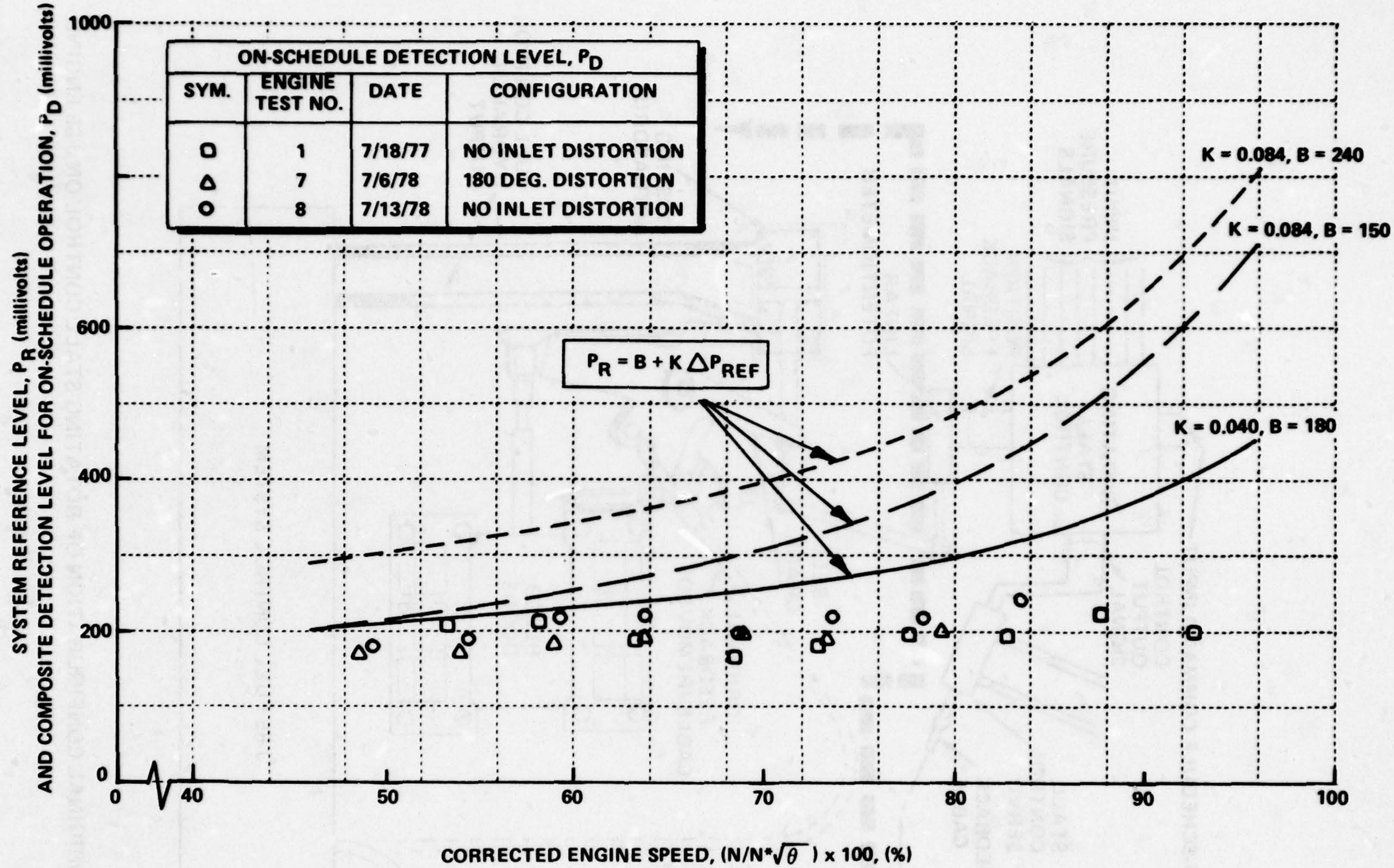


Figure 5 SYSTEM REFERENCE LEVELS USED IN STALL CONTROL TESTS ON J-85 ENGINE

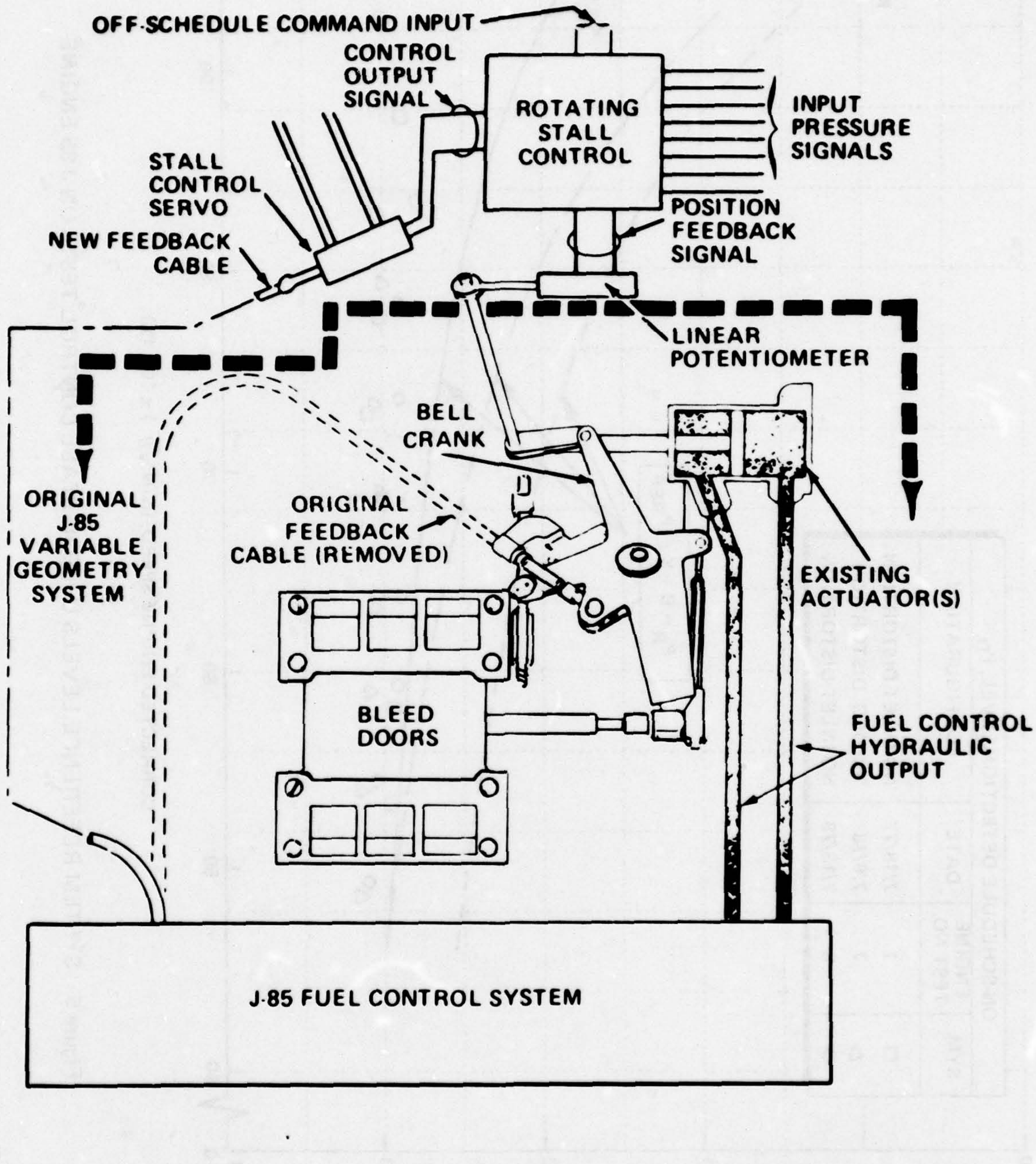


Figure 6 ORIGINAL CONFIGURATION OF ROTATING STALL CONTROL ON J-85 ENGINE

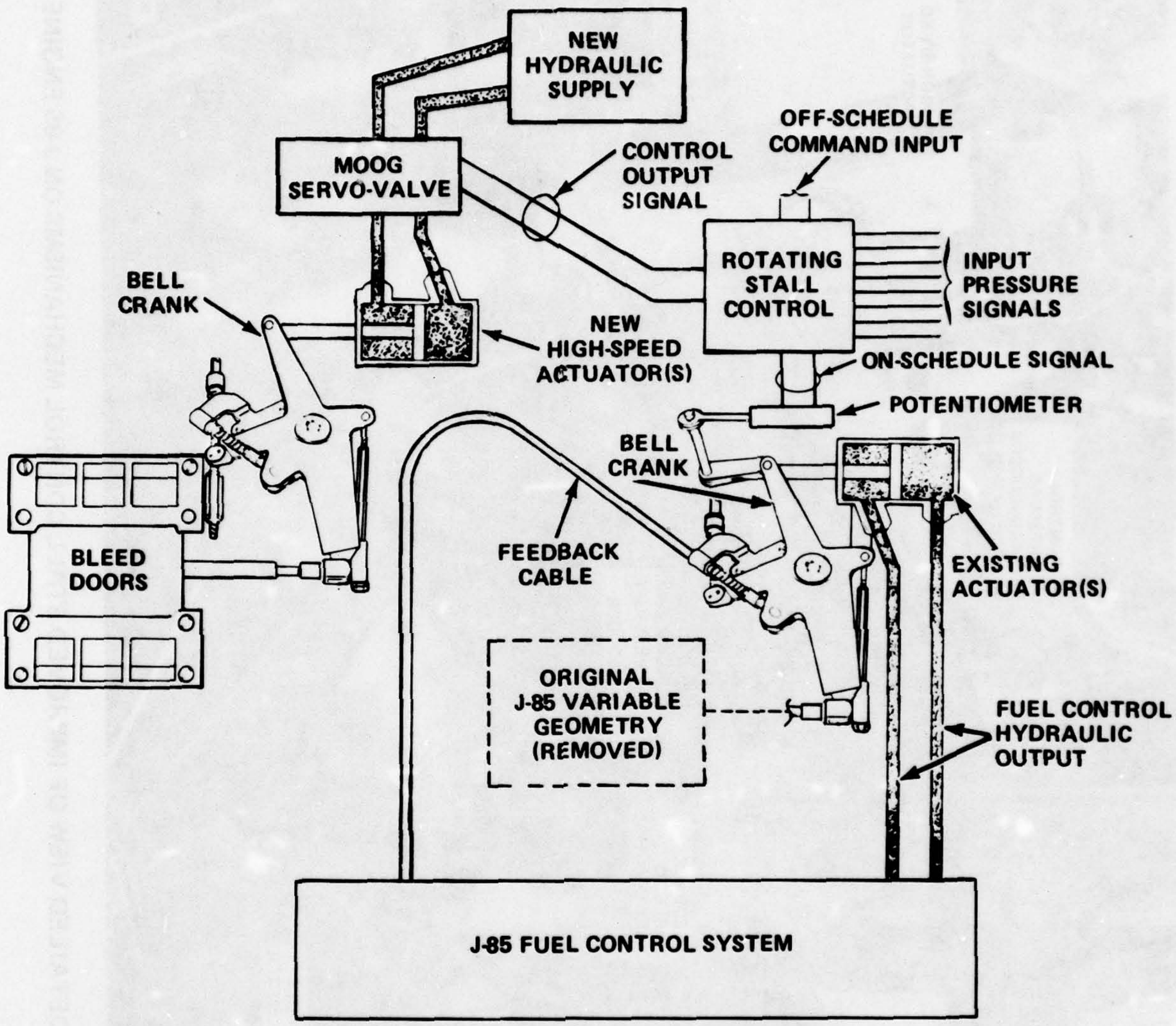


Figure 7 CONFIGURATION OF STALL CONTROL ON J-85 ENGINE USED TO OBTAIN RAPID RESPONSE TO STALL INCEPTION

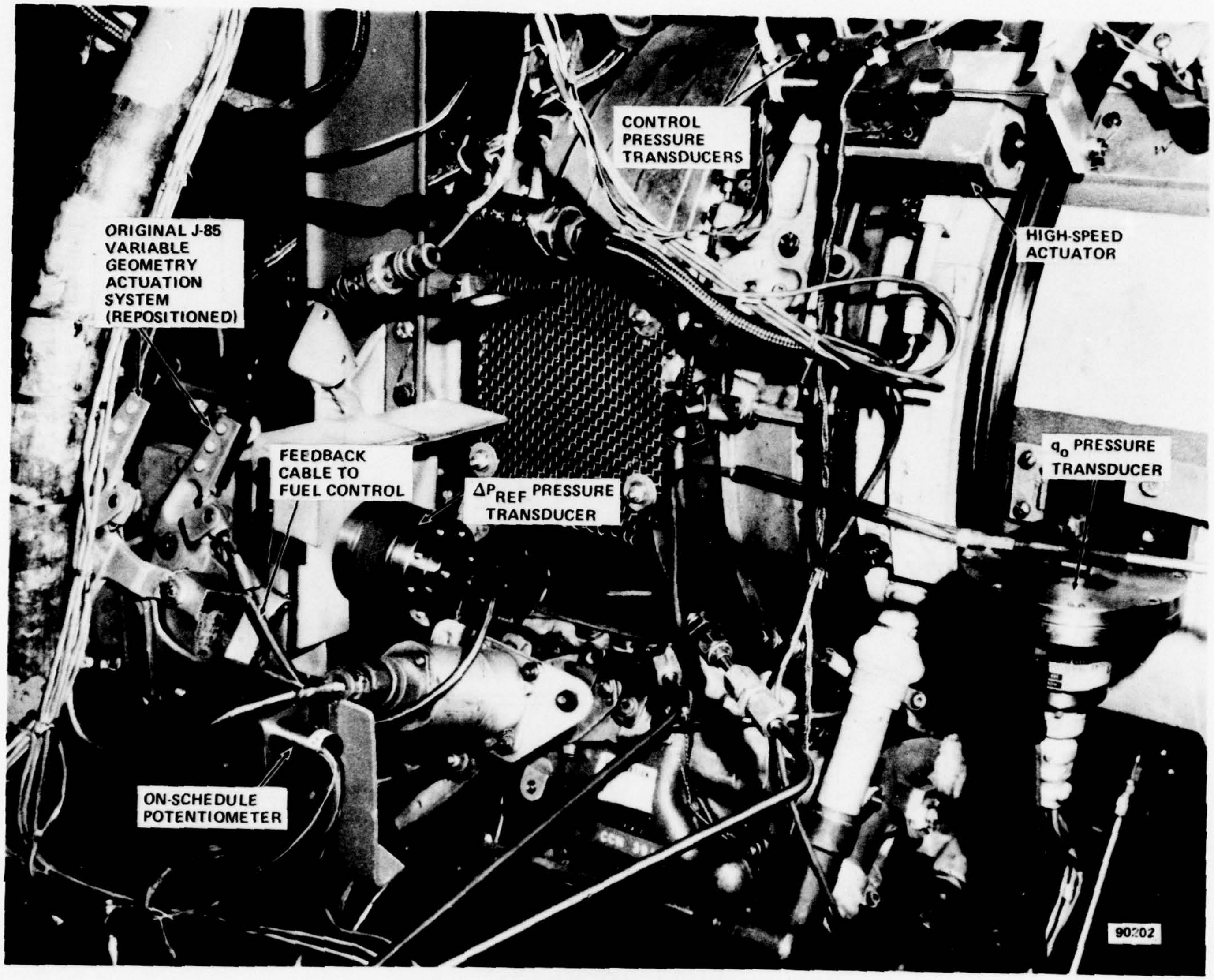


Figure 8 DETAILED VIEW OF IMPROVED STALL CONTROL MECHANISMS ON J-85 ENGINE

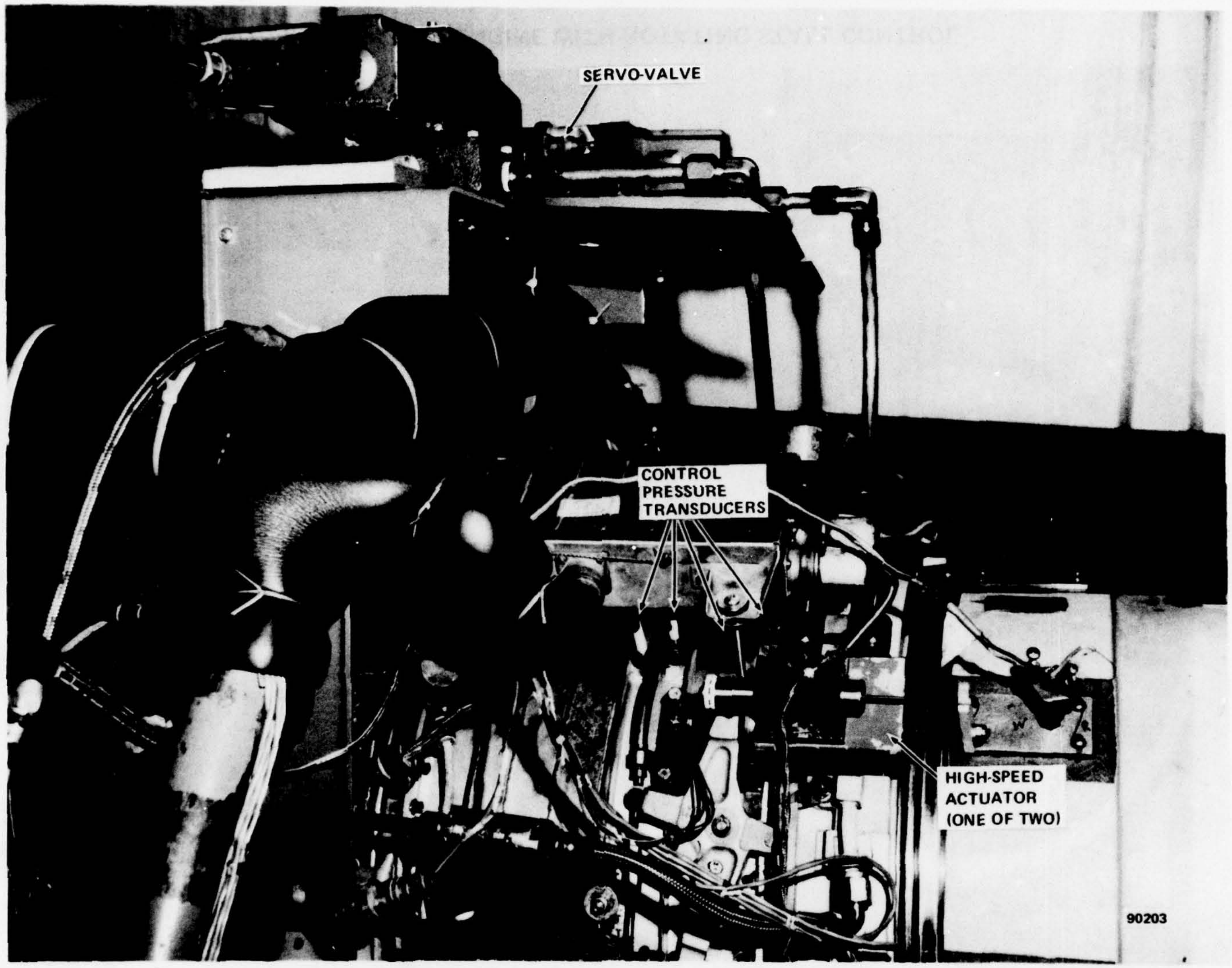


Figure 9 VIEW OF HIGH-SPEED ACTUATION SYSTEM AND SEVERAL STALL CONTROL PRESSURE TRANSDUCERS

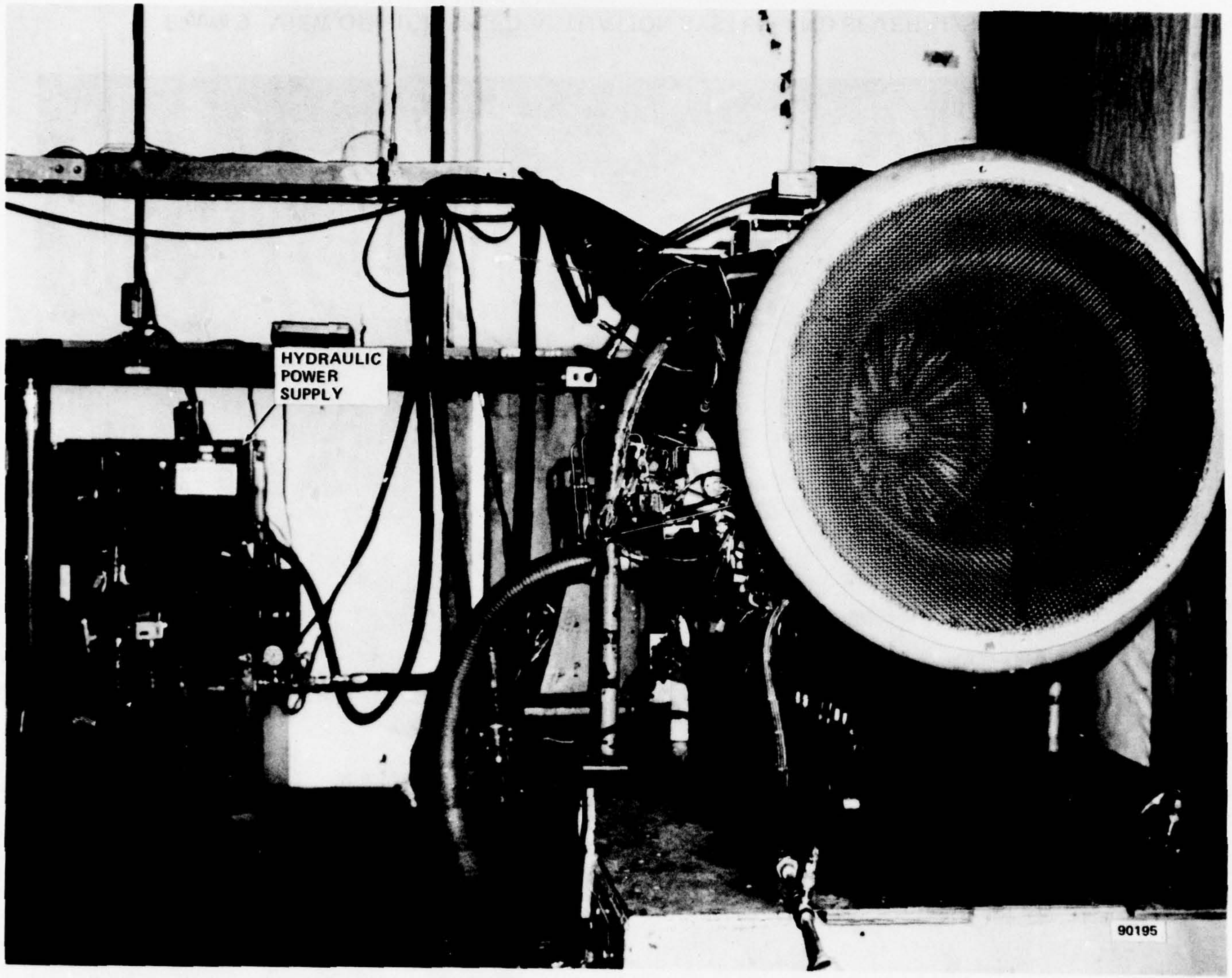


Figure 10 J-85 ENGINE WITH ROTATING STALL CONTROL

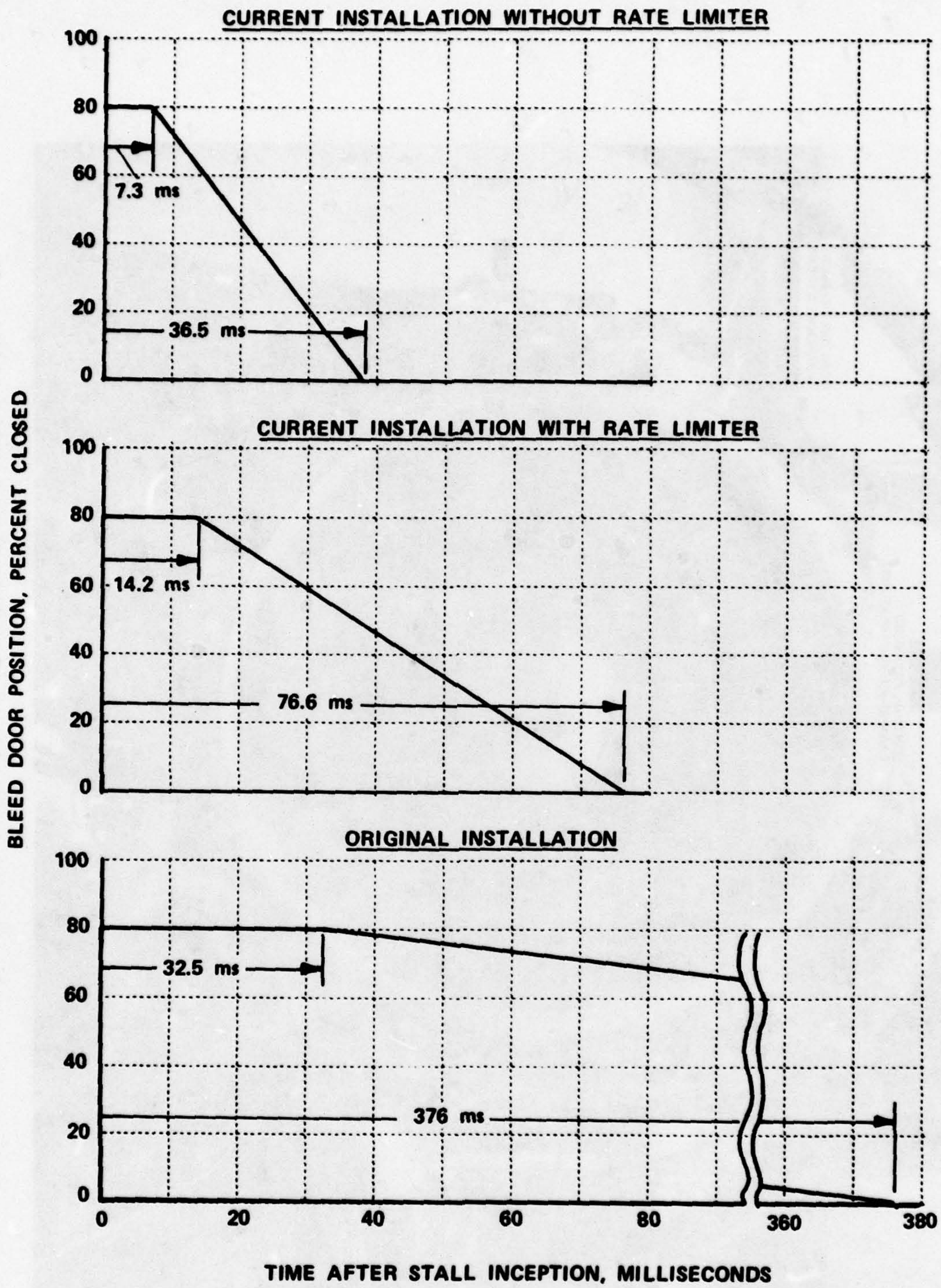


Figure 11 COMPARISON OF J-85 BLEED DOOR RESPONSE RATES TO LARGE AMPLITUDE ROTATING STALL STARTING AT BLEED DOORS 80 PERCENT CLOSED

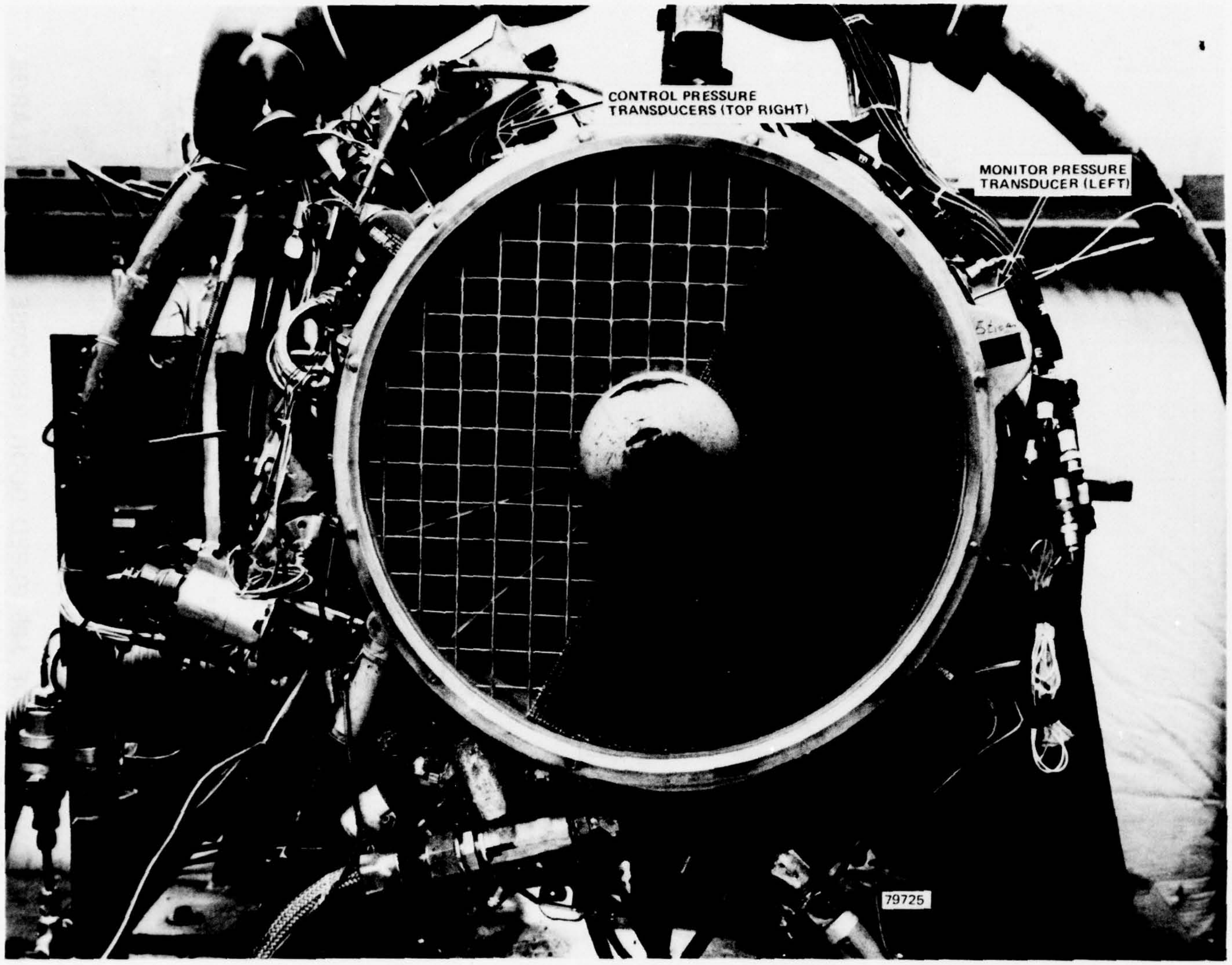


Figure 12 FRONT VIEW OF J-85 ENGINE WITH 180° DISTORTION SCREEN INSTALLED

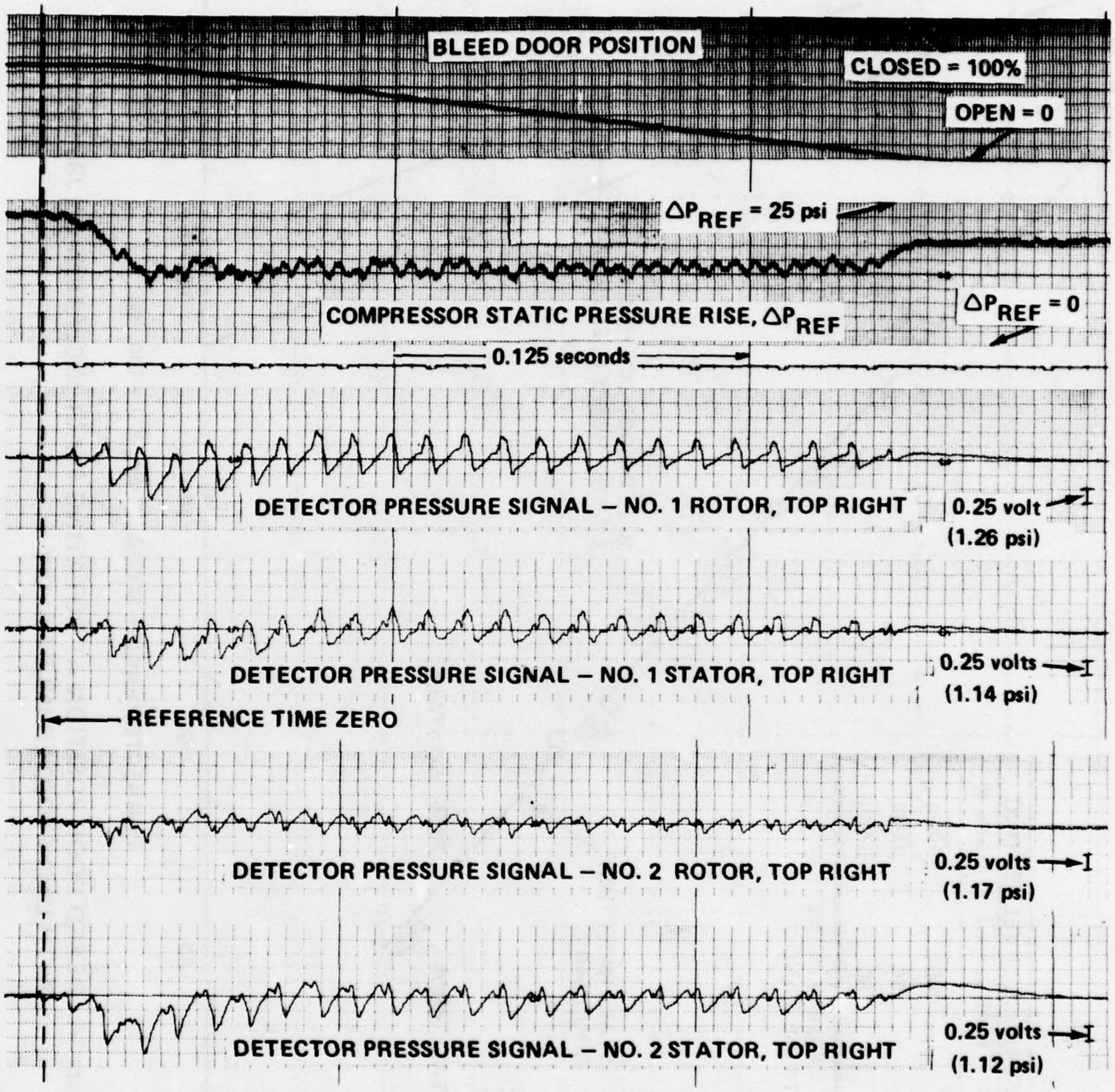


Figure 13 PERFORMANCE OF ORIGINAL STALL CONTROL INSTALLATION ON J-85 ENGINE (EXPANDED TIME SCALE), 180° CIRCUMFERENTIAL INLET DISTORTION, CORRECTED ENGINE SPEED ($N/N*\sqrt{\theta}$) = 71.8%

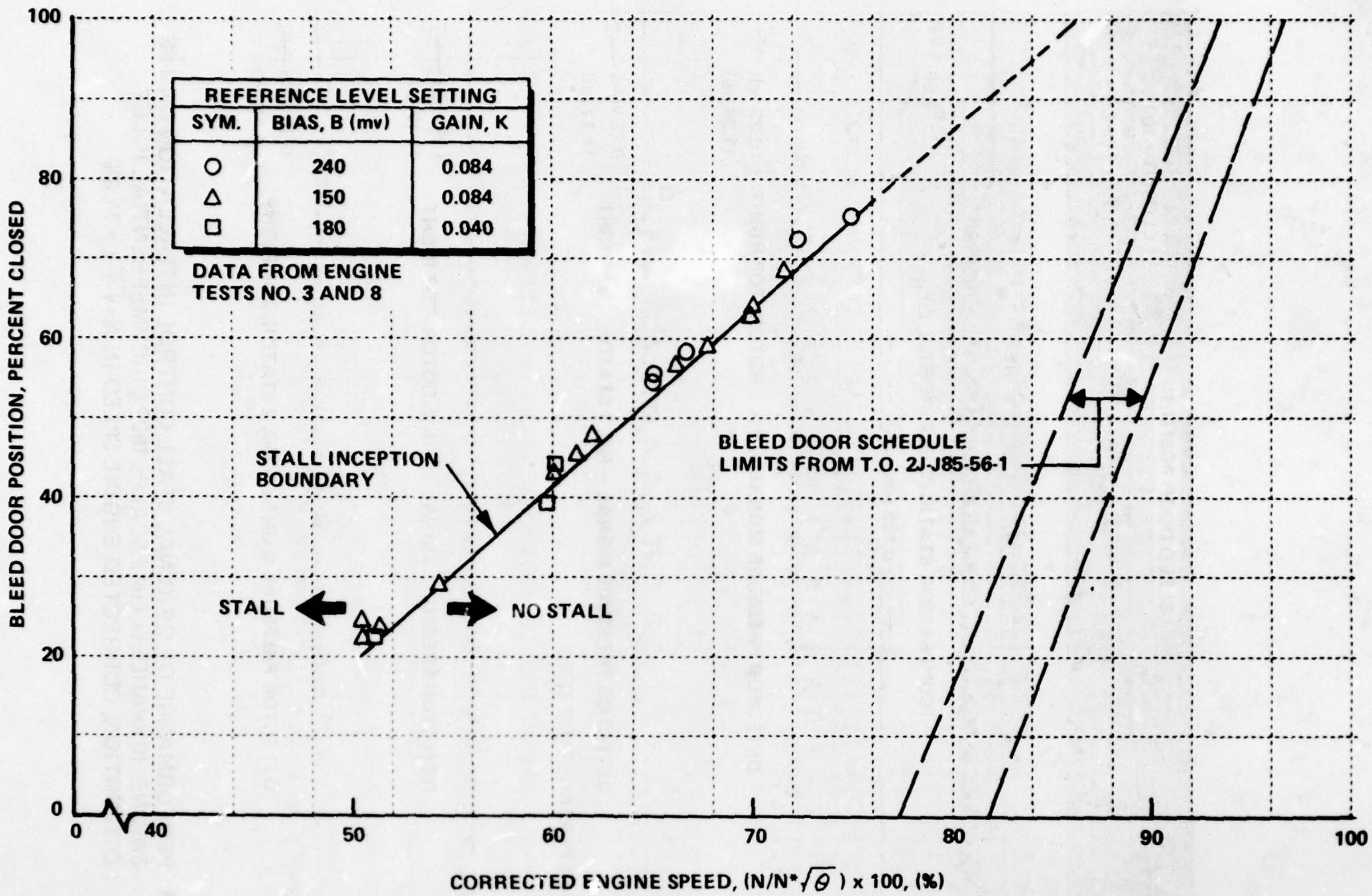


Figure 14 BLEED DOOR POSITION AT ROTATING STALL INCEPTION ON J85 ENGINE WITH UNDISTORTED INLET FLOW

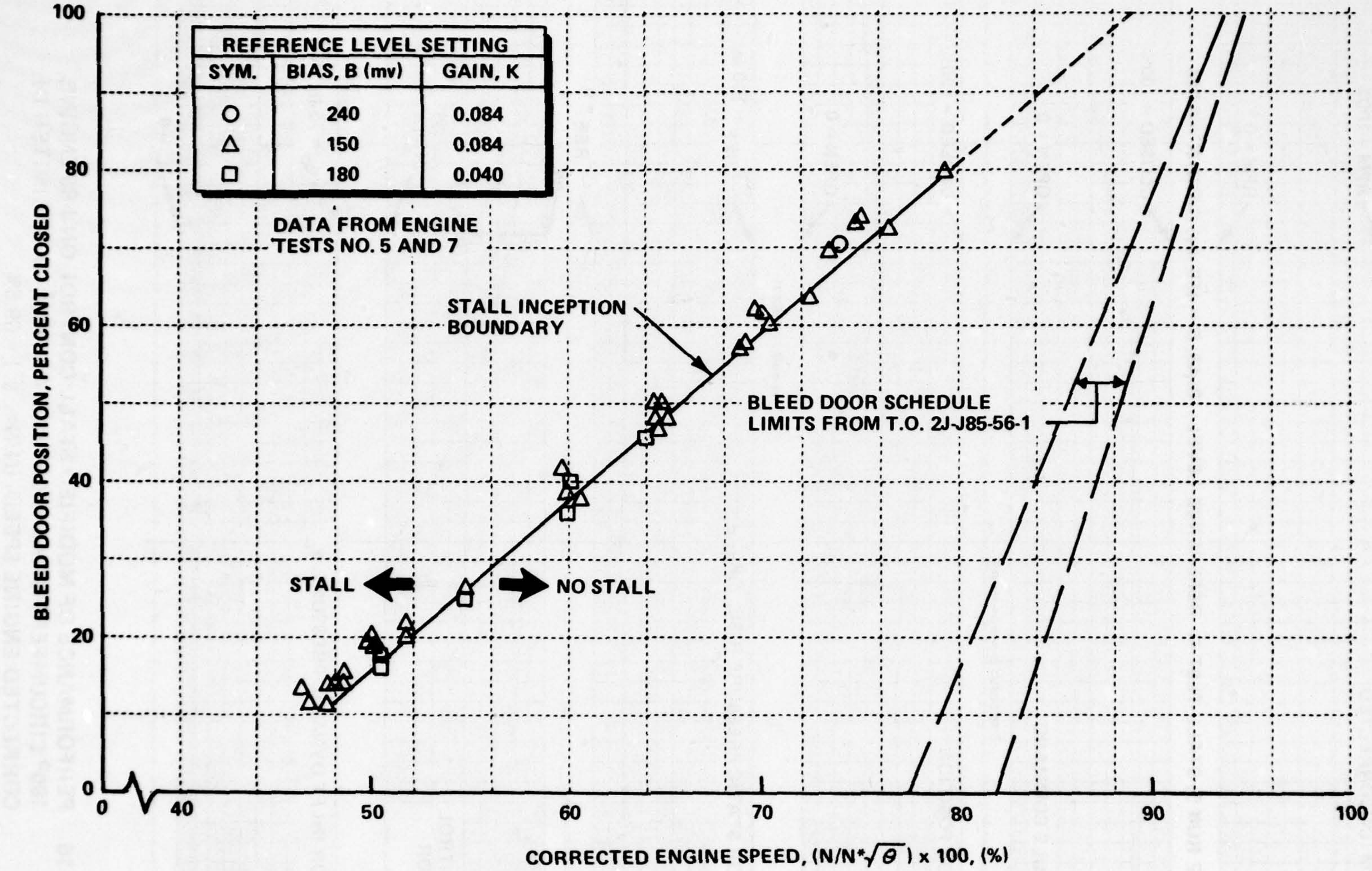


Figure 15 BLEED DOOR POSITION AT ROTATING STALL INCEPTION ON J85 ENGINE WITH 180 DEGREE CIRCUMFERENTIAL INLET DISTORTION

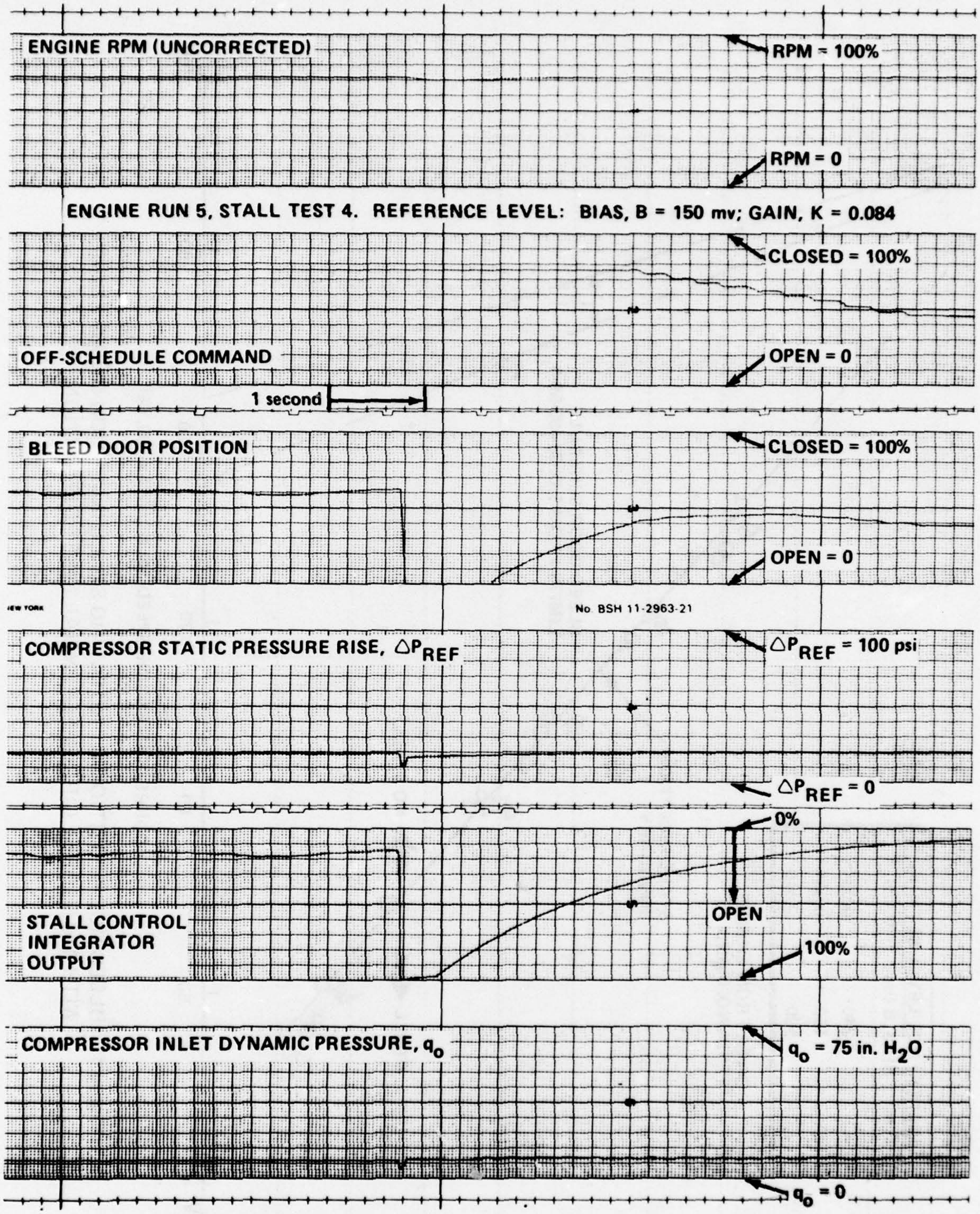


Figure 16 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE 180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER IN CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}) = 69.5\%$

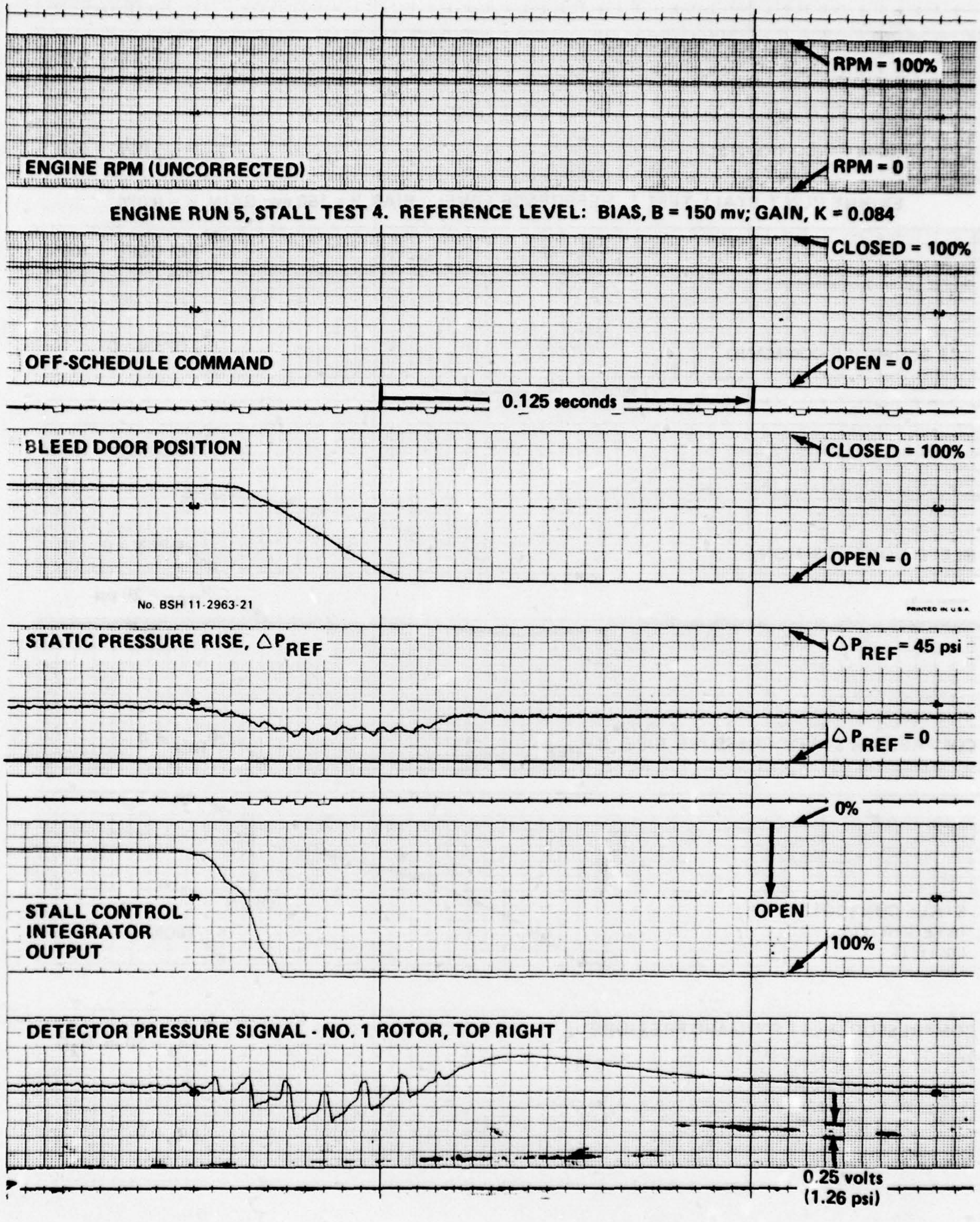


Figure 17 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE) 180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER IN CORRECTED ENGINE SPEED, $(N/N* \sqrt{\theta})$ = 69.5%

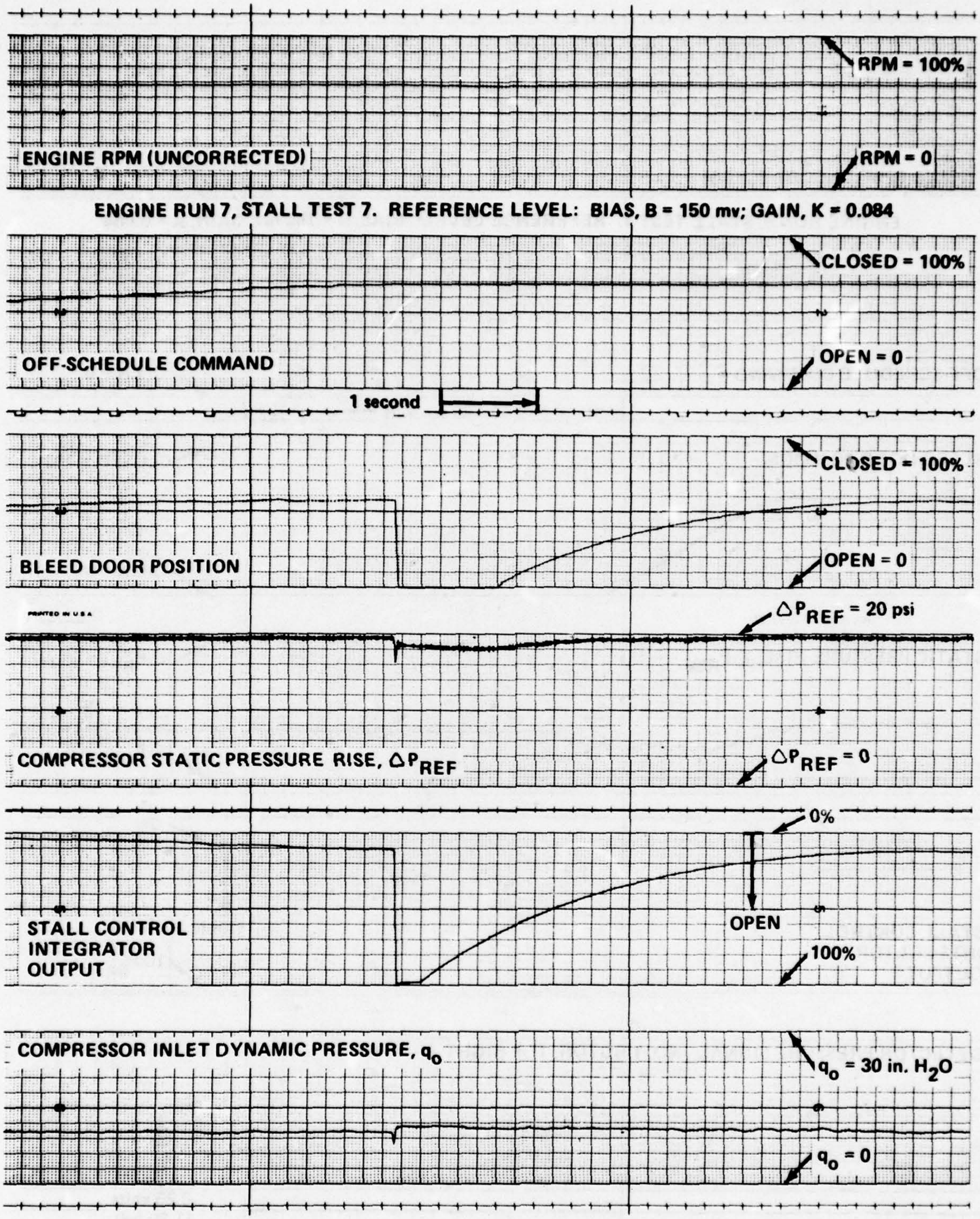


Figure 18 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE
180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta})$ = 69.1%

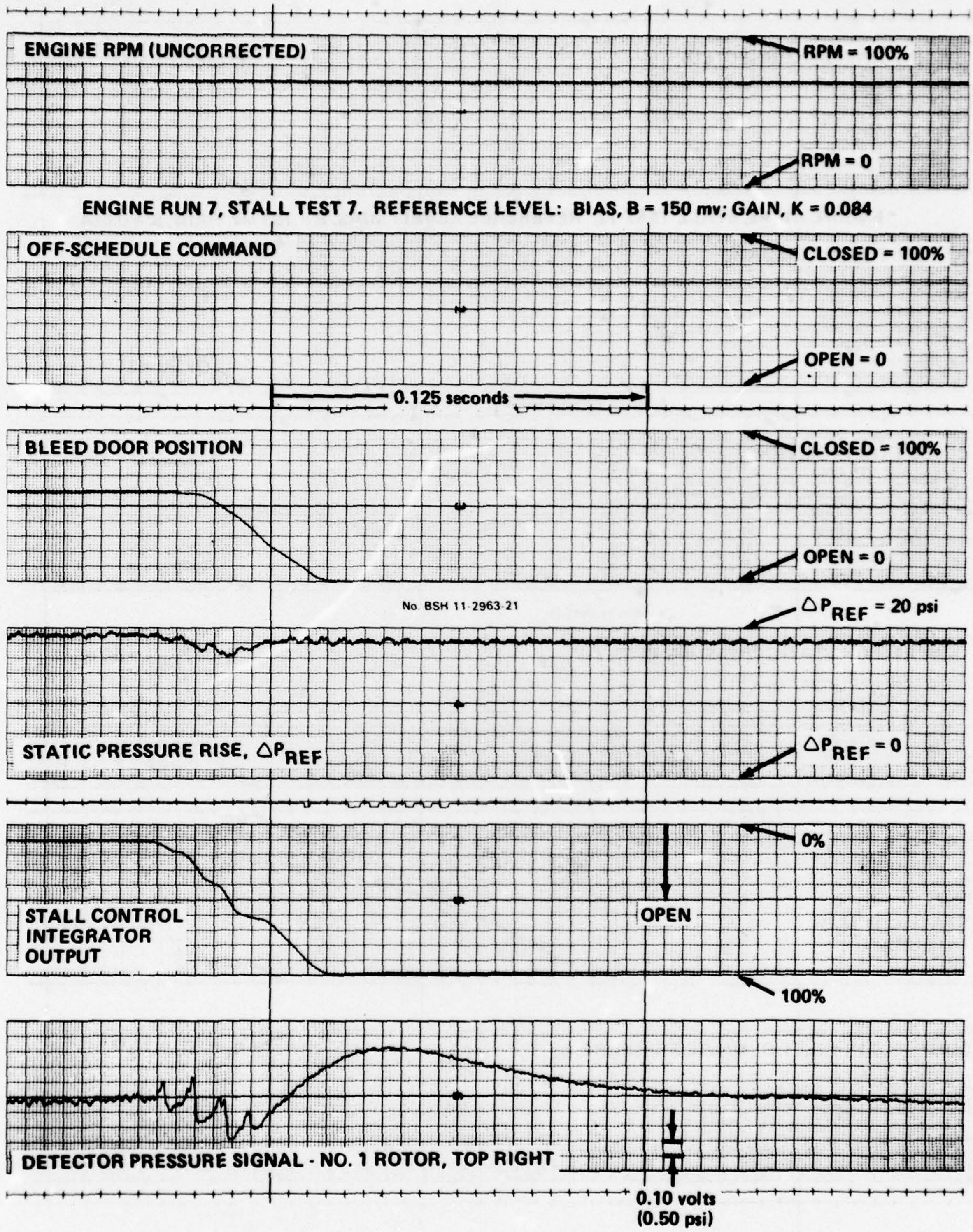


Figure 19 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE)
180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}) = 69.1\%$

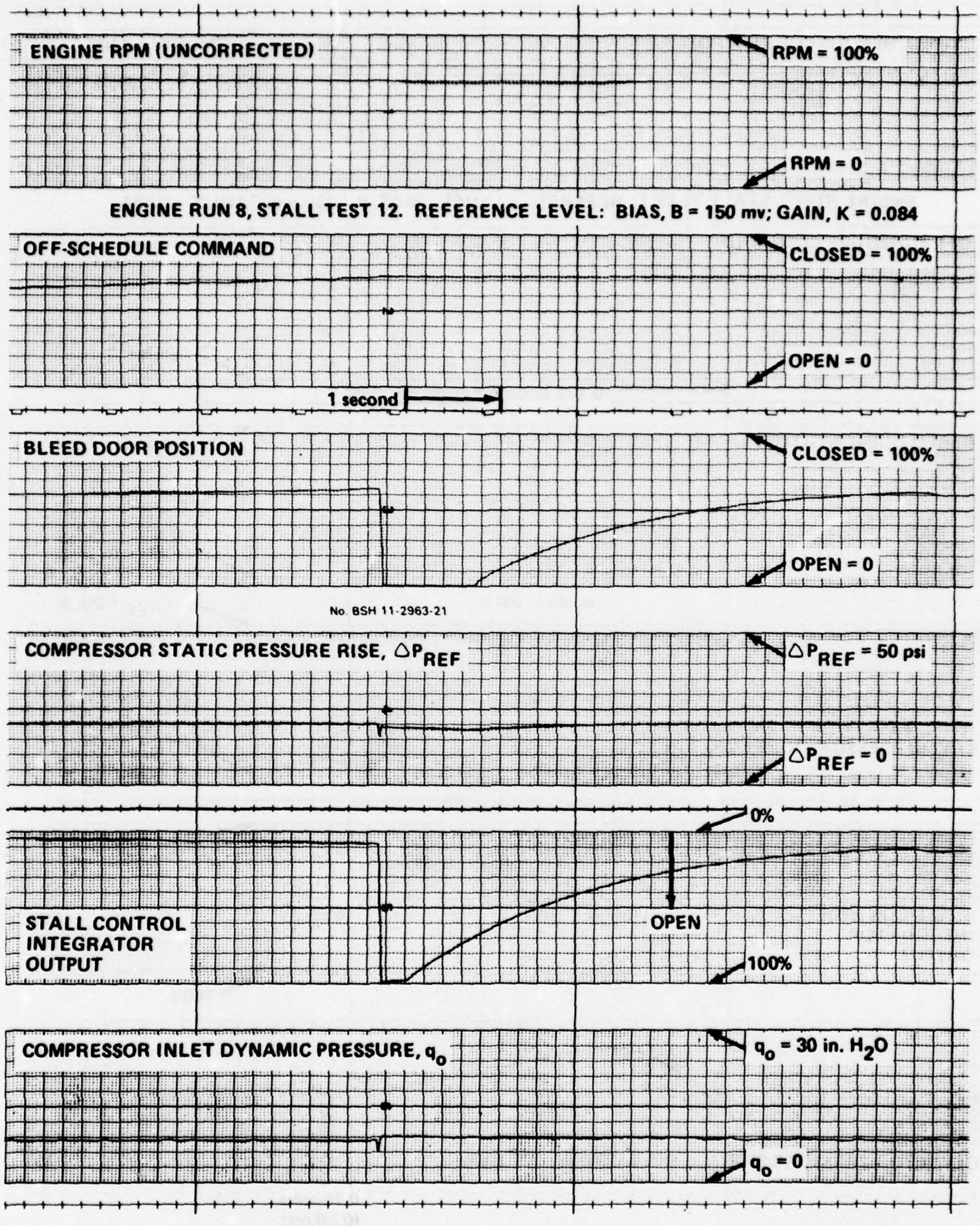


Figure 20 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE
NO INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED = 69.9%

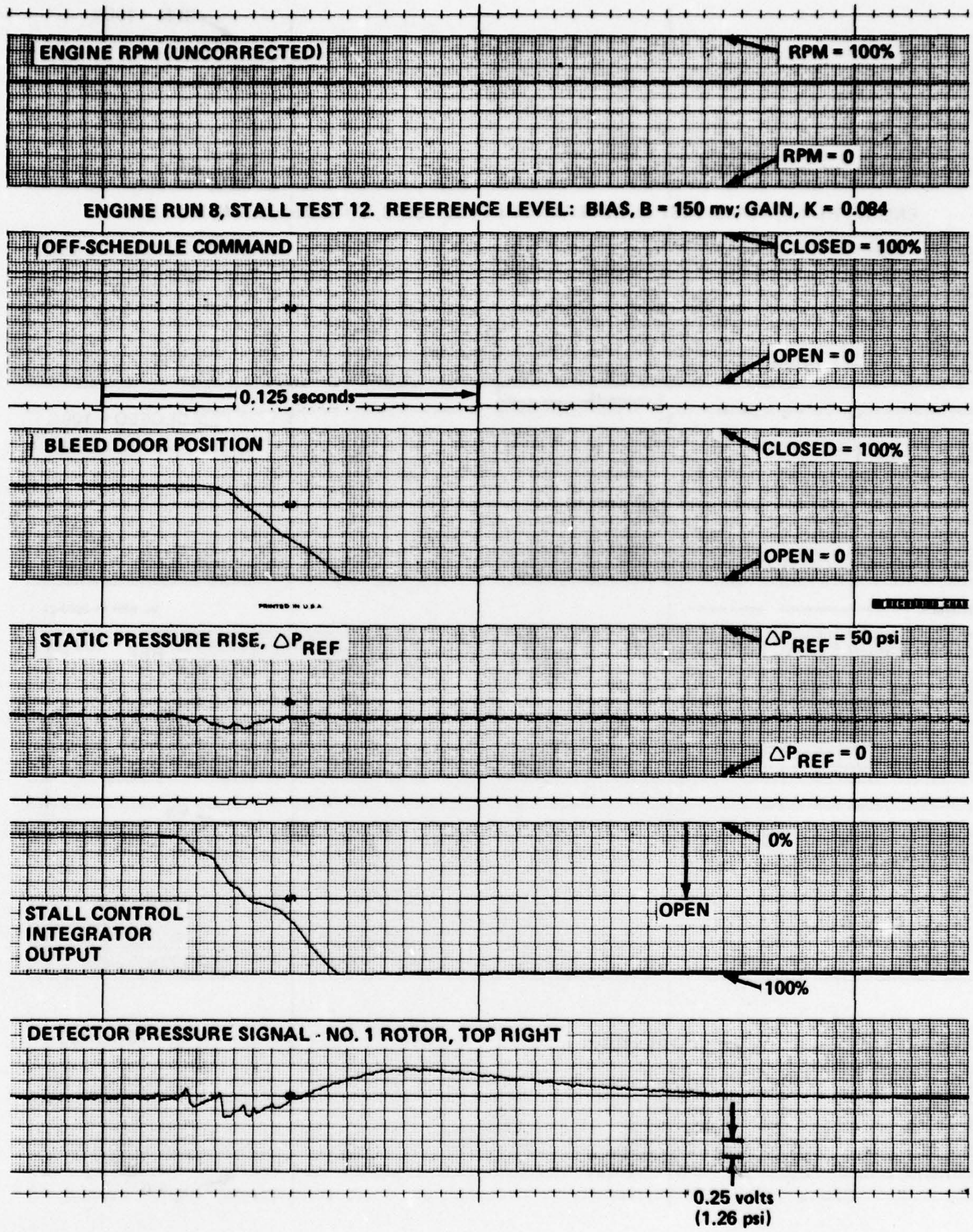


Figure 21 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE)
NO INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta})$ = 69.9%

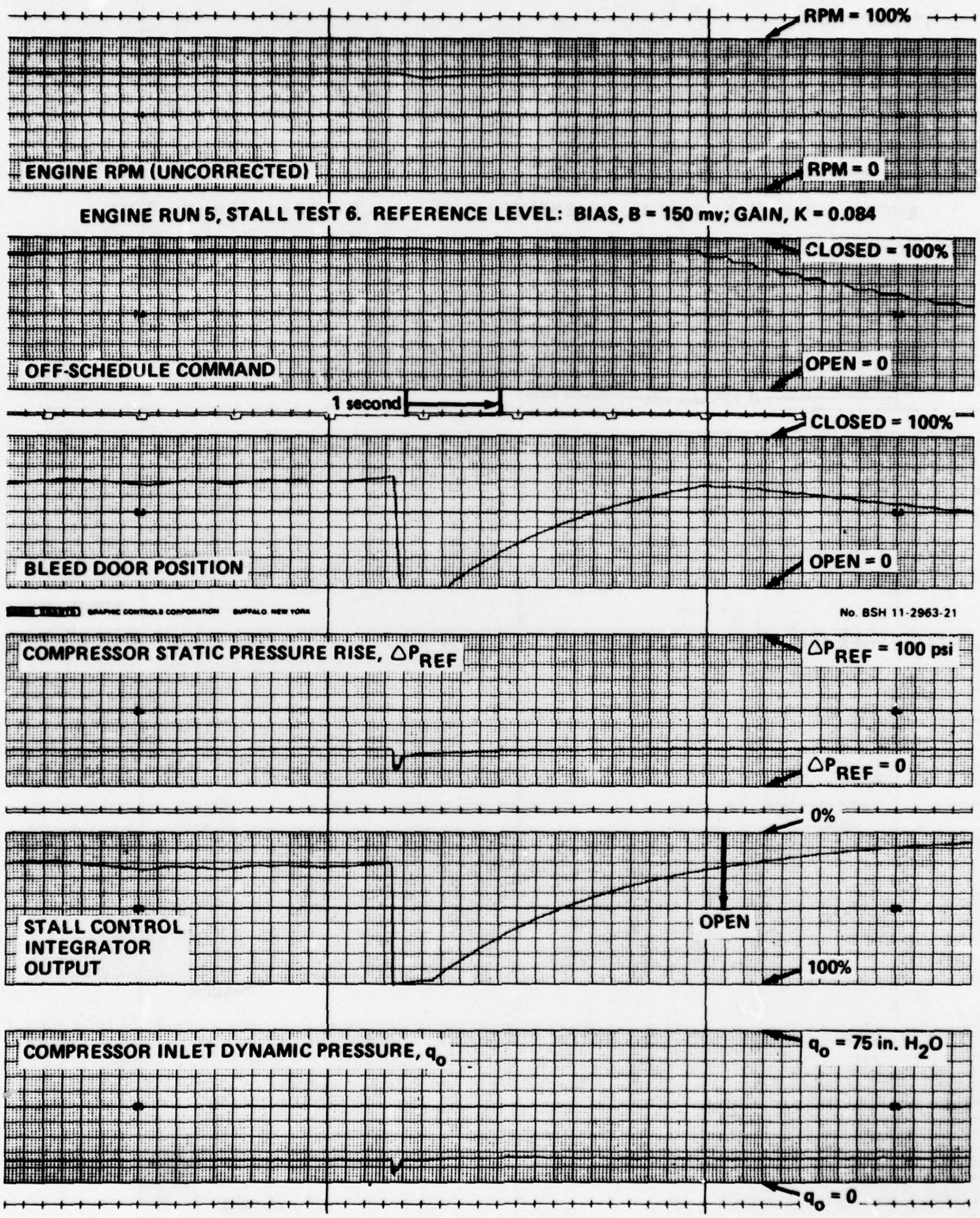


Figure 22 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE 180^o CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER IN CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}) = 74.9\%$

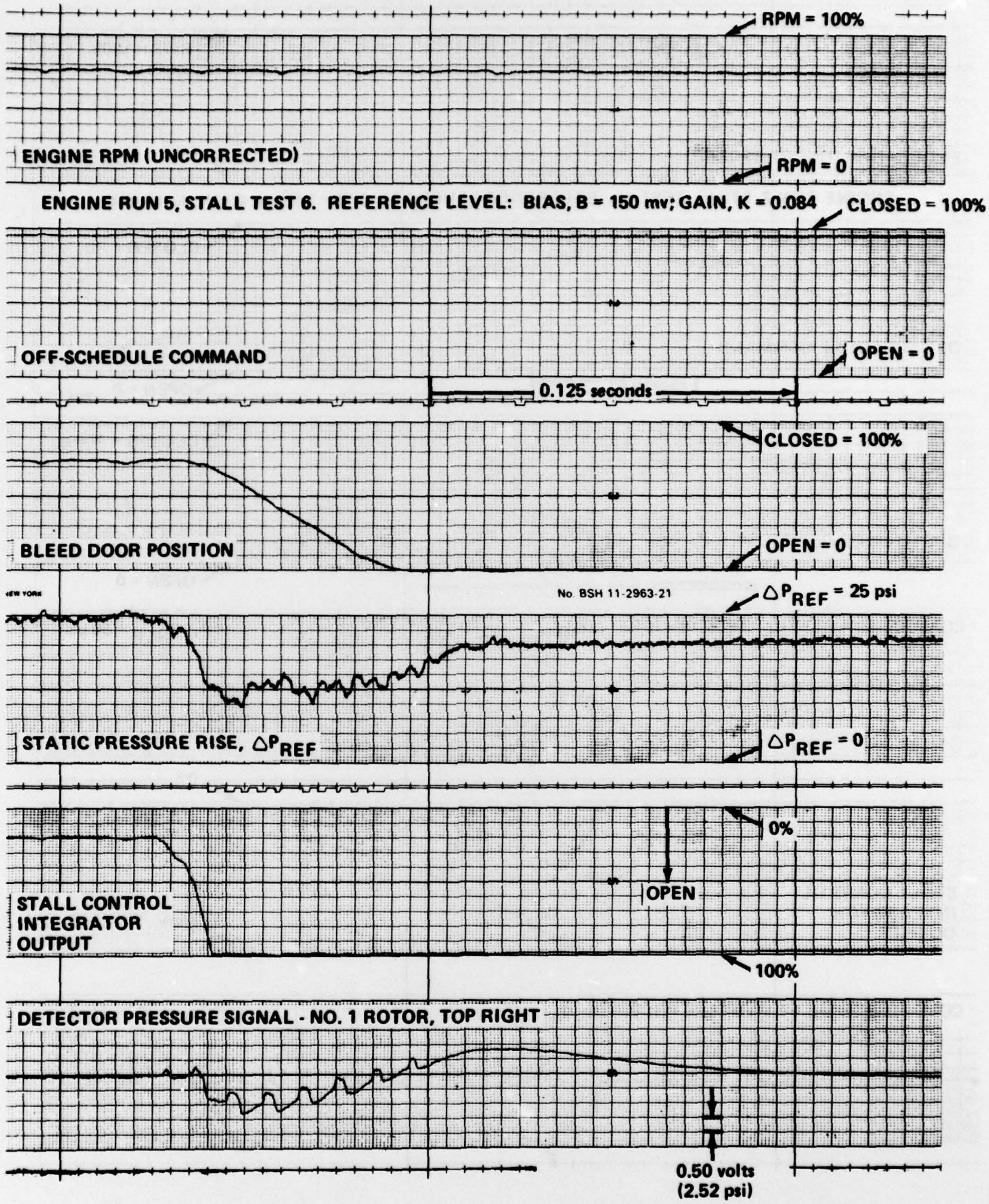


Figure 23 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE) 180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER IN CORRECTED ENGINE SPEED, $((N/N*\sqrt{\theta}) = 74.9\%$

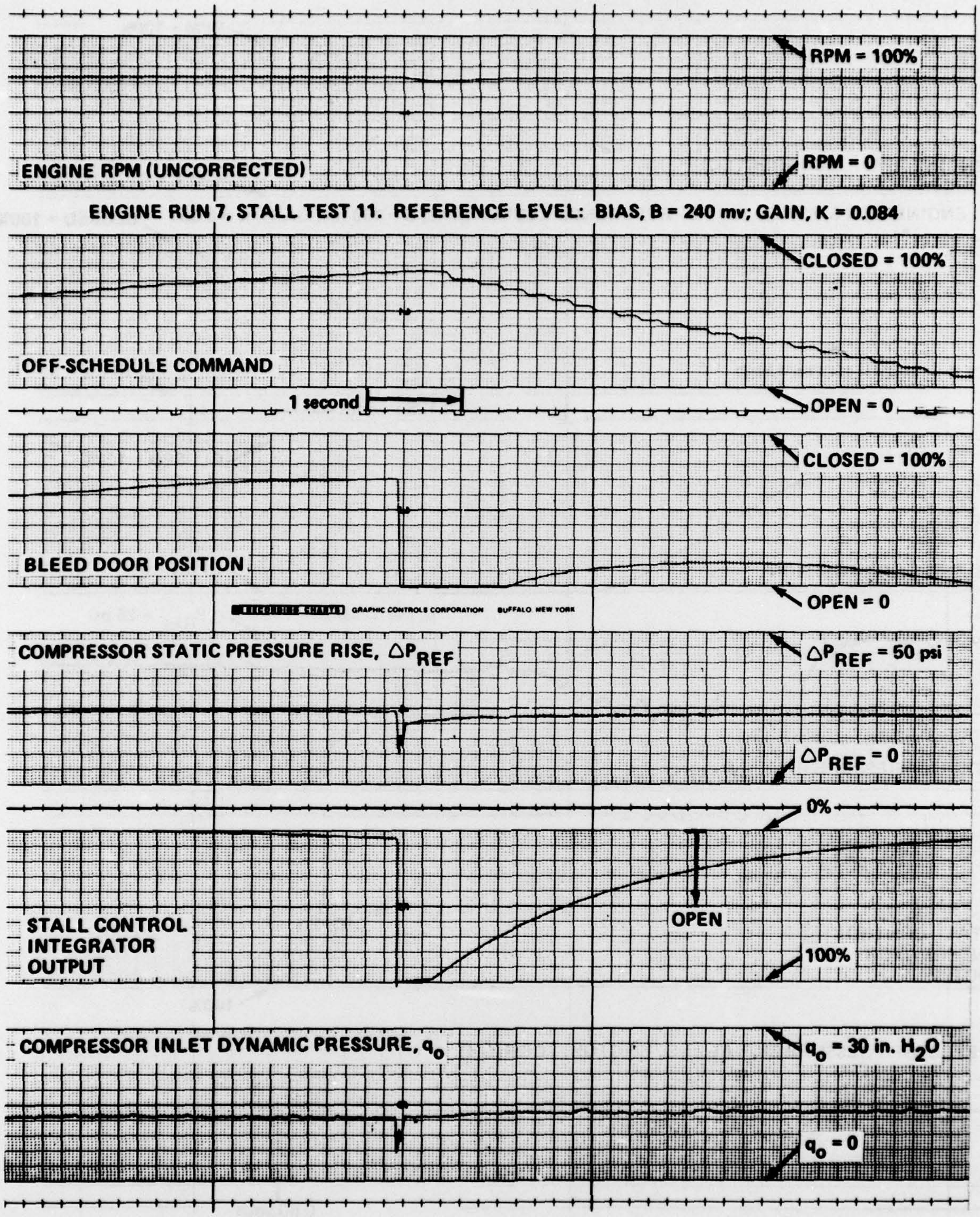


Figure 24 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE 180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER OUT CORRECTED ENGINE SPEED, $(N/N^* \sqrt{\theta}) = 74.0\%$

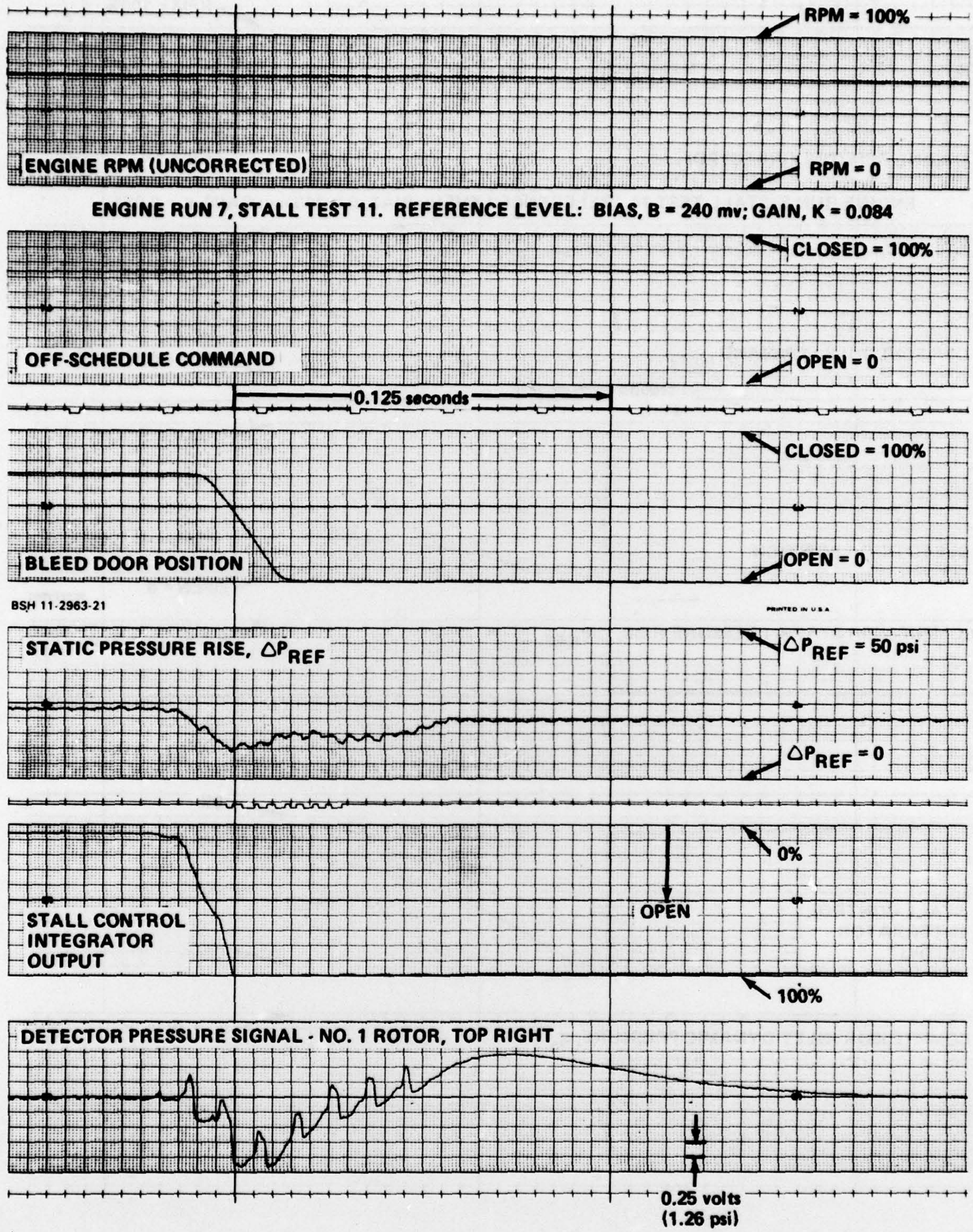


Figure 25 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE)
180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}\,)$ = 74.0%

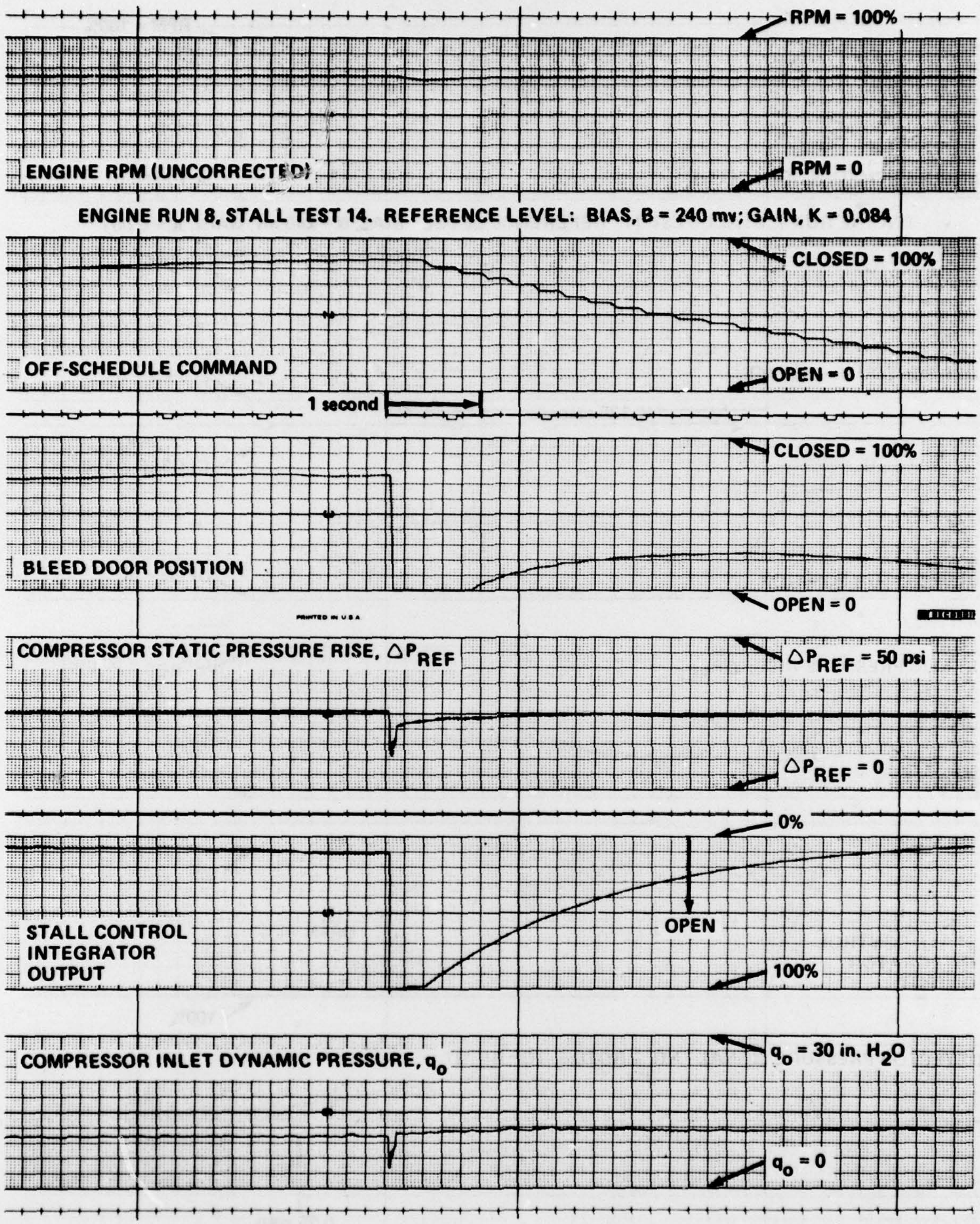


Figure 26 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE NO INLET DISTORTION, RATE LIMITER OUT CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta})$ = 75.0%

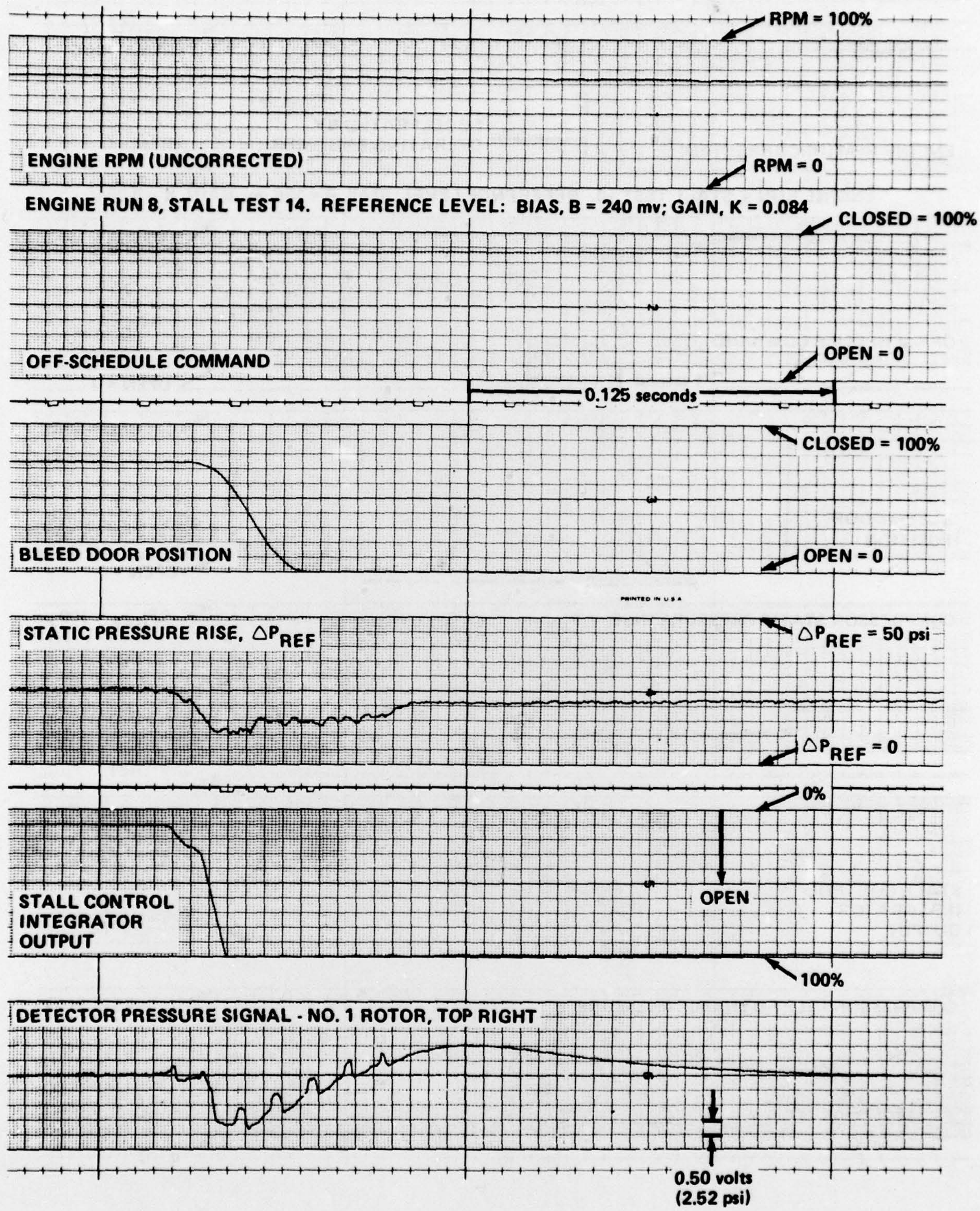


Figure 27 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE)
NO INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}) = 75.0\%$

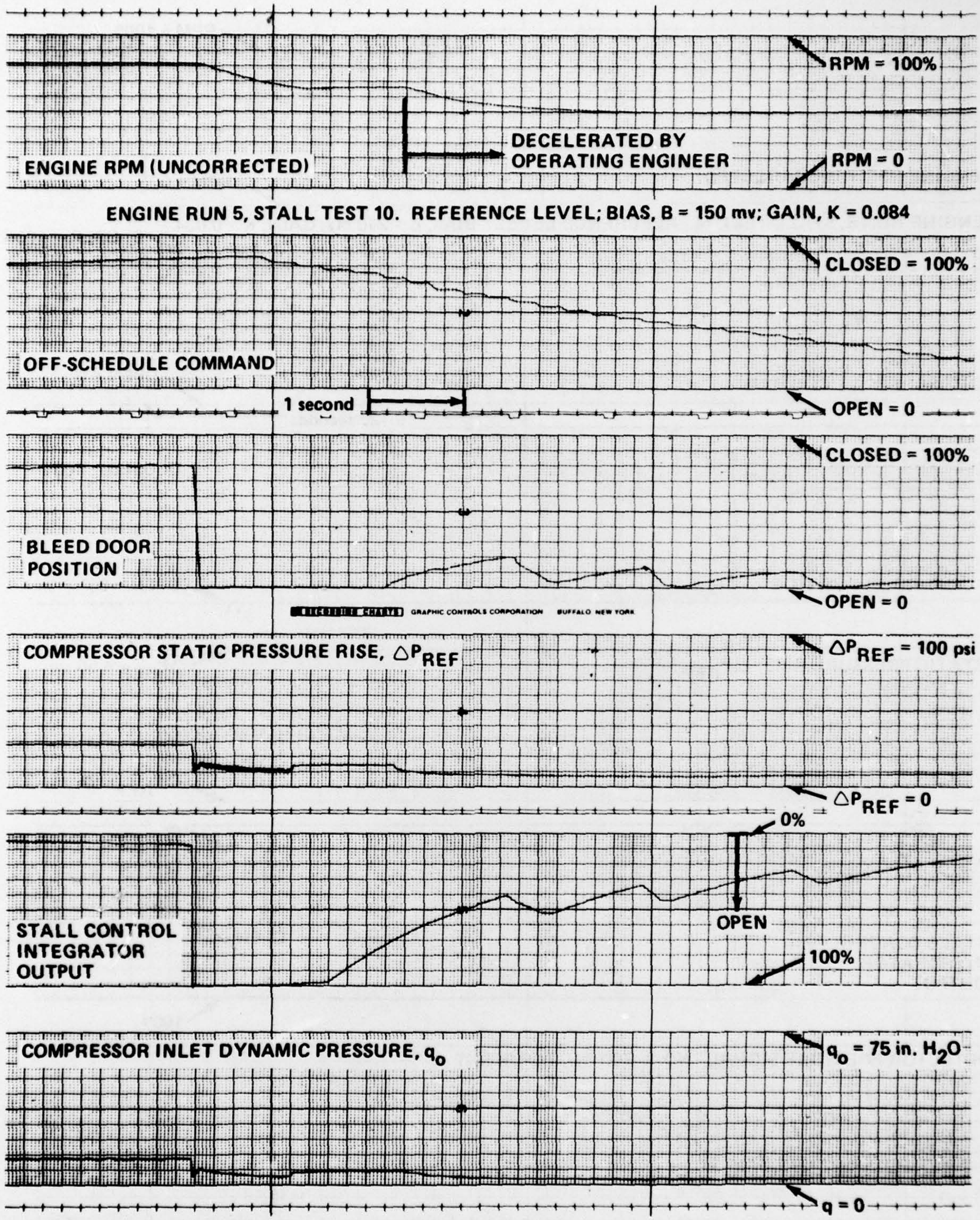


Figure 28 PERFORMANCE OF MODIFIED STALL CONTROL ON J-85 ENGINE 180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER IN CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta})$ = 79.4%

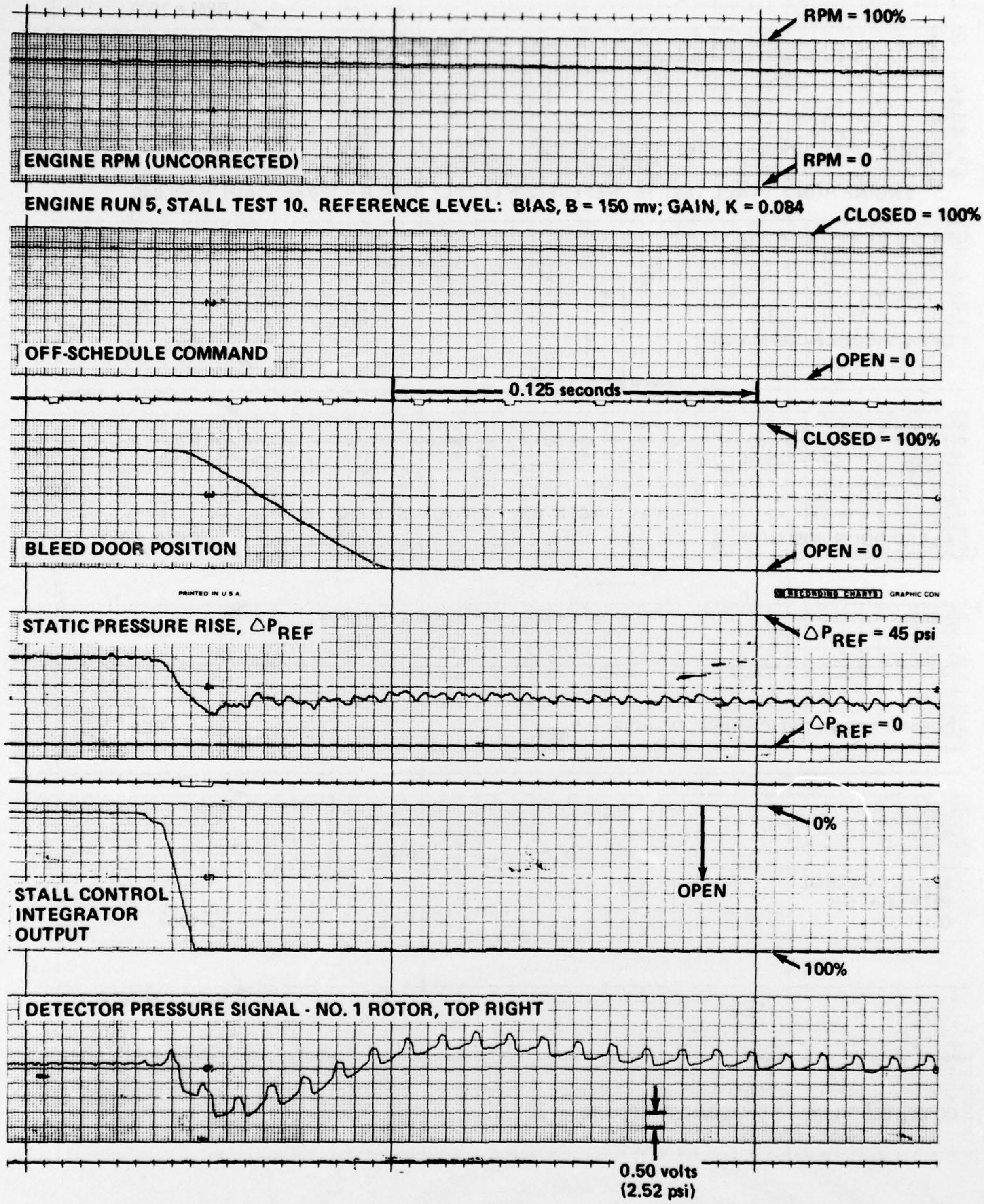


Figure 29 STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE) 180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER IN CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta})$ = 79.4%

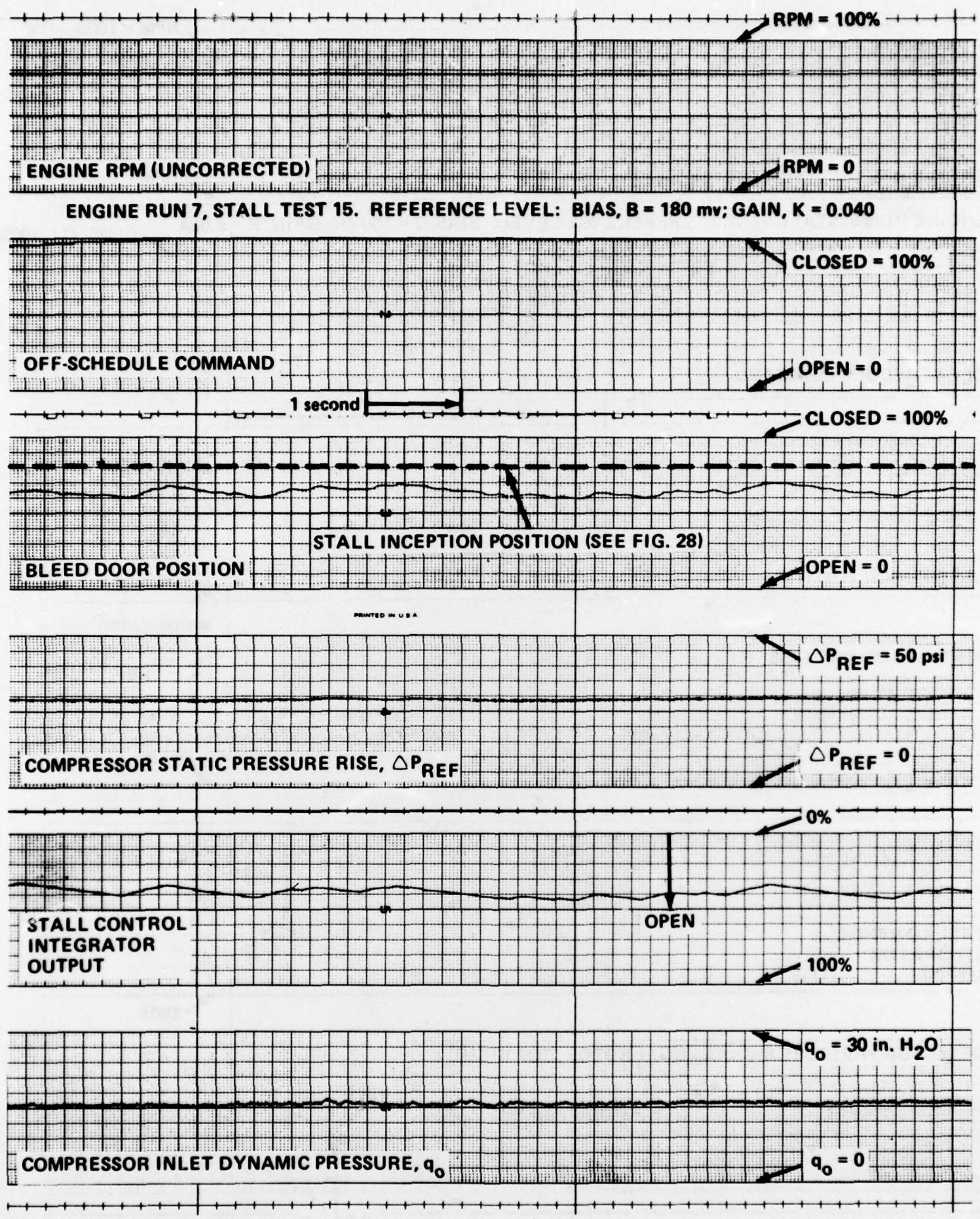


Figure 30 ELIMINATION OF ROTATING STALL BY MODIFIED STALL CONTROL SYSTEM
180° CIRCUMFERENTIAL INLET DISTORTION, RATE LIMITER OUT
CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}) = 78.7\%$

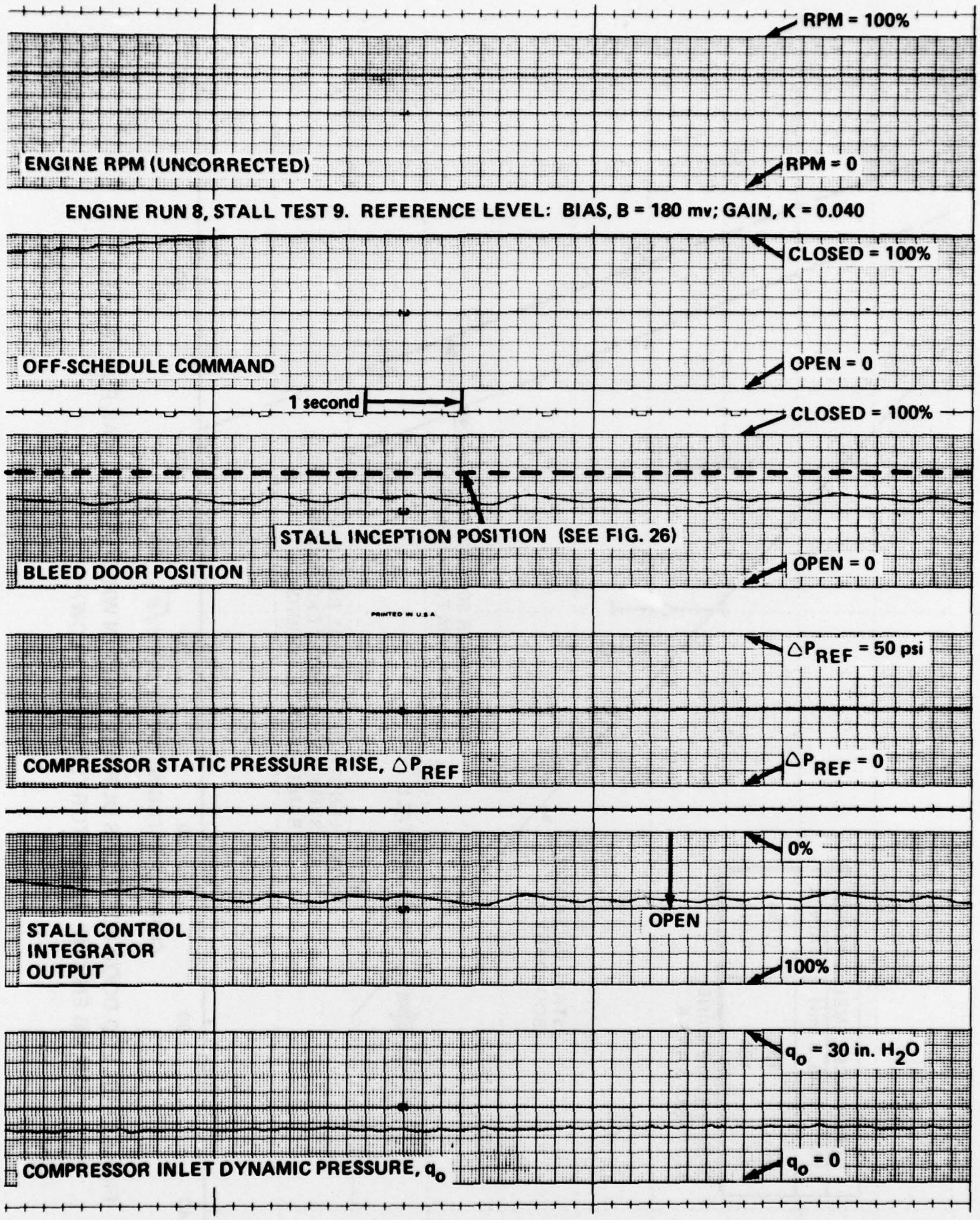


Figure 31 ELIMINATION OF ROTATING STALL BY MODIFIED STALL CONTROL SYSTEM - NO INLET DISTORTION, RATE LIMITER OUT CORRECTED ENGINE SPEED, $(N/N*\sqrt{\theta}\,)$ = 75.0%

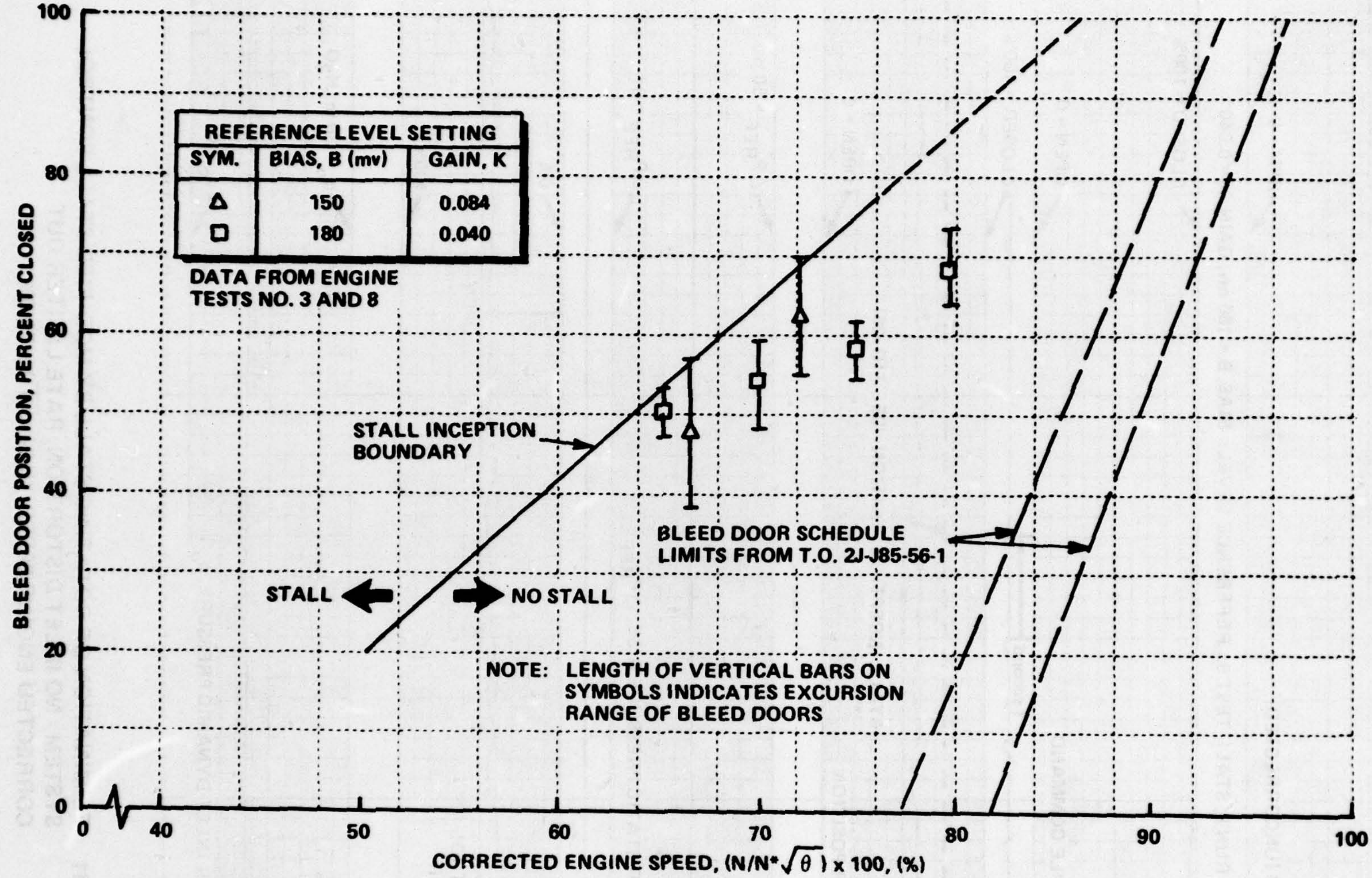


Figure 32 BLEED DOOR POSITIONS DURING TESTS IN WHICH STALL WAS ELIMINATED ON J85 ENGINE (UNDISTORTED INLET FLOW)

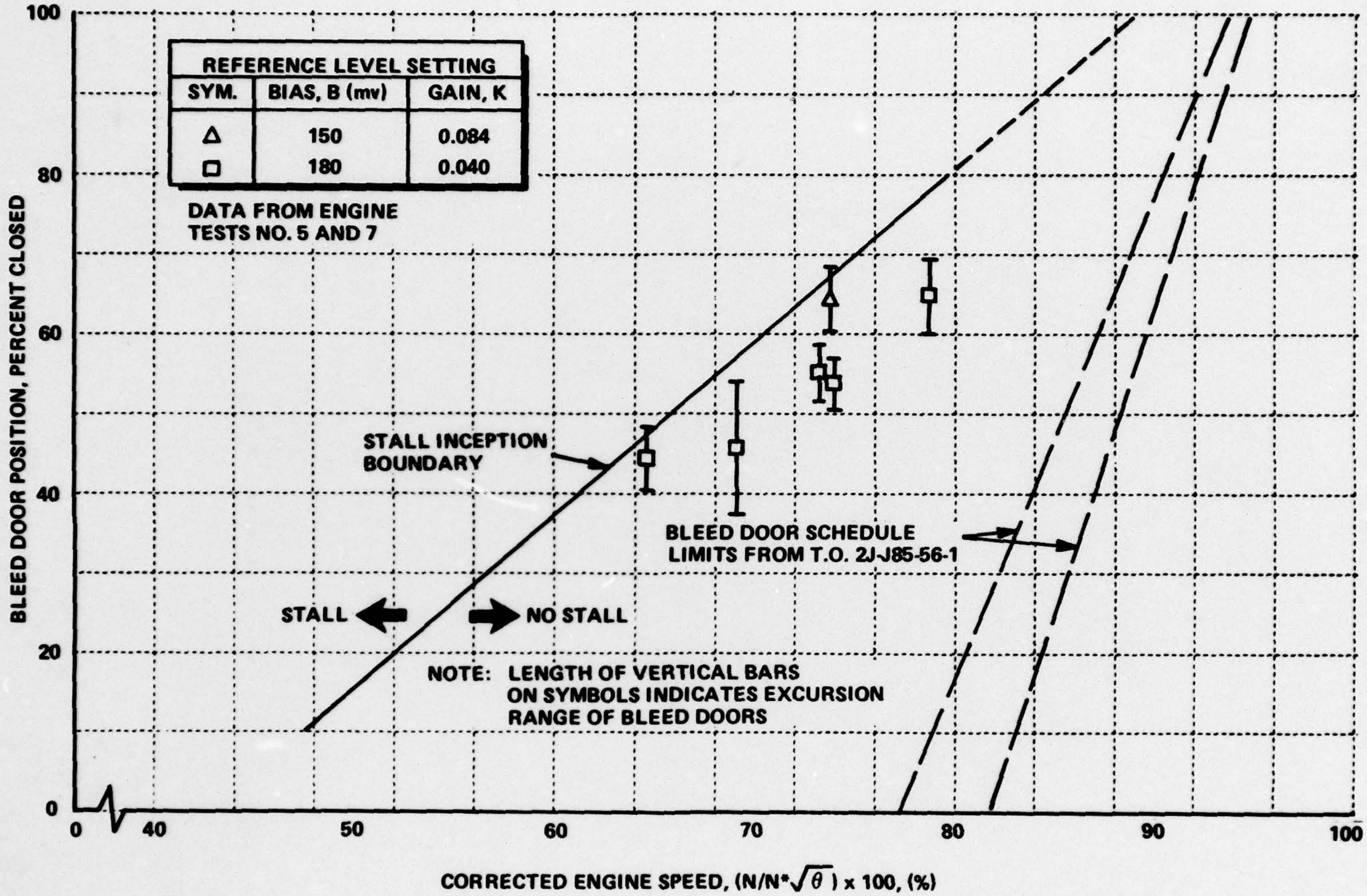


Figure 33 BLEED DOOR POSITIONS DURING TESTS IN WHICH STALL WAS ELIMINATED ON J85 ENGINE (180 DEGREE CIRCUMFERENTIAL INLET DISTORTION)

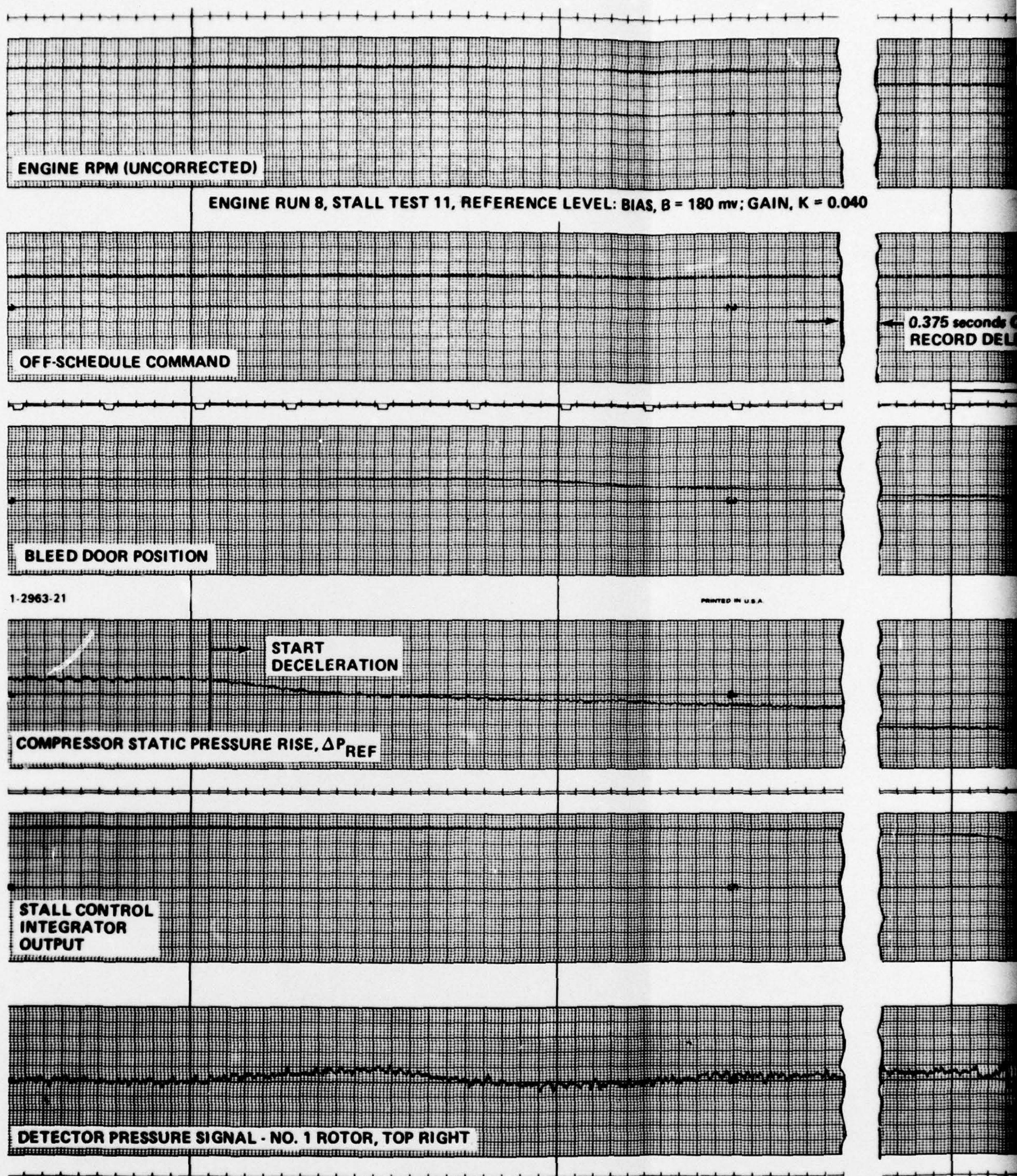
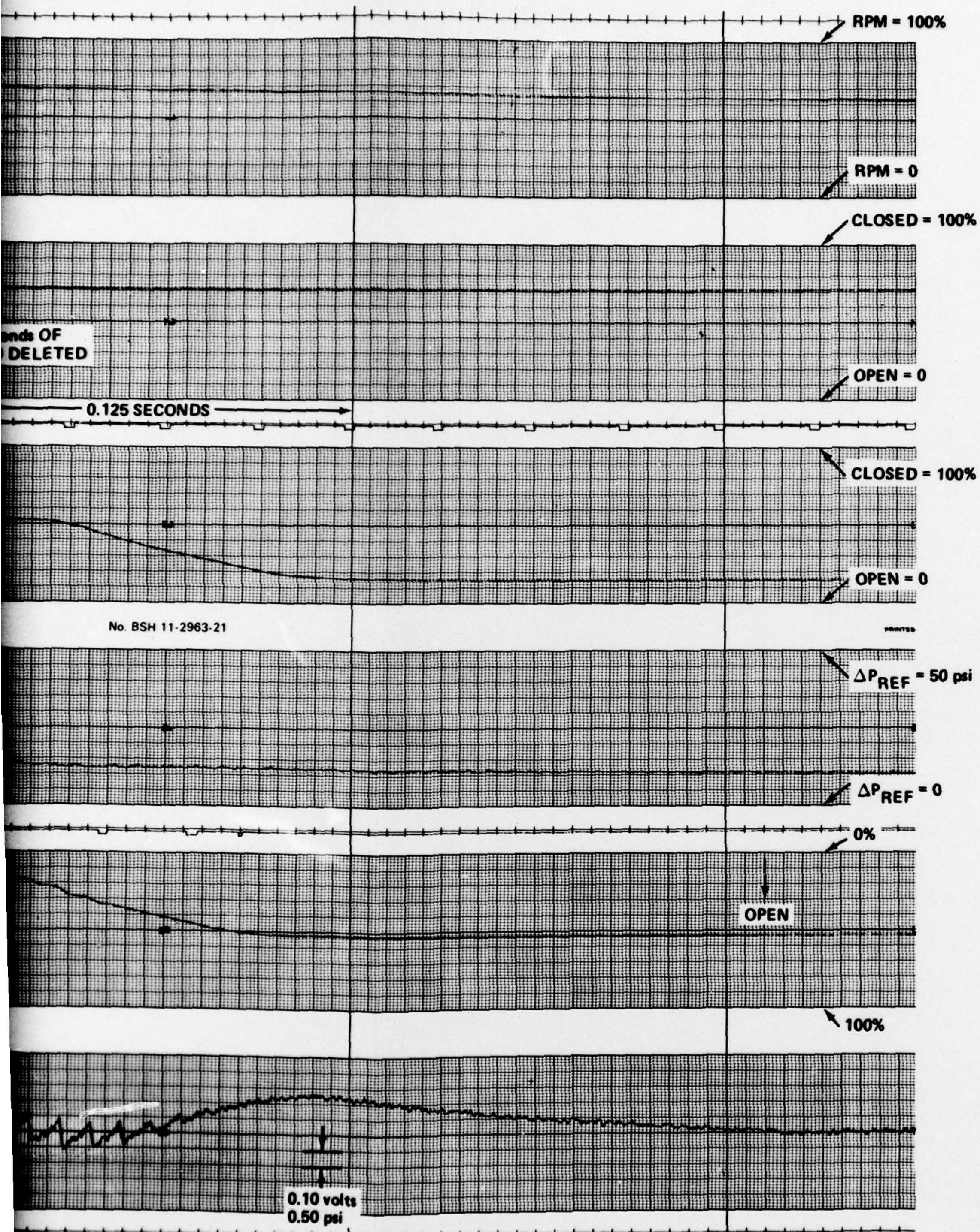


Figure 34 **STALL CONTROL PERFORMANCE (EXPANDED TIME SCALE) NO INLET DISTORTION, RATE LIMITER OUT, COMPRESSOR STALLED BY DECELERATING ENGINE WITH BLEED DOORS PARTLY CLOSED**



RPM = 100%
RPM = 0
CLOSED = 100%
...nds OF
... DELETED
OPEN = 0
0.125 SECONDS
CLOSED = 100%
OPEN = 0
No. BSH 11-2963-21
ΔP_{REF} = 50 psi
ΔP_{REF} = 0
0%
OPEN
100%
0.10 volts
0.50 psi

.1

2

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2. Ludwig, G.R. and Nenni, J.P. "A Rotating Stall Control System for Turbojet Engines", ASME Paper 78-GT-115, ASME Gas Turbine Conference, London, England, April 9-13, 1978.

3. Small, Lester L. "J-85 Engine Evaluation of a Rotating Stall Detection and Control System", AFAPL Technical Report - to be published.

4. Calogeras, J.E., Mehalic, C.M., and Burstadt, P.L., "Experimental Investigation of the Effect of Screen-Induced Total Pressure Distortion on Turbojet Stall Margin", NASA Technical Memorandum TMS-2239, March 1971.

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